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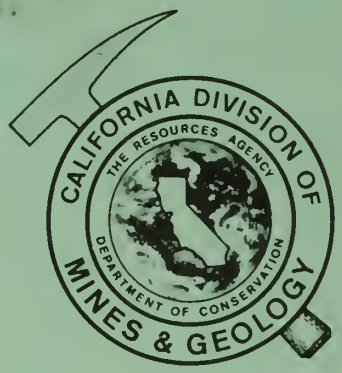
1978

CALIFORNIA DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 137



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SPECIAL REPORT 137

SAN GREGORIO - HOSGRI FAULT ZONE, CALIFORNIA

Eli A. Silver and William R. Normark
Editors

1978

CALIFORNIA DIVISION OF MINES AND GEOLOGY
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FOREWORD

Special Report 137 of the California Division of Mines and Geology is a collection of papers originally presented as part of a symposium on the San Gregorio–Hosgri fault zone at the 1977 Cordilleran section meeting of the Geological Society of America in Sacramento.

Publishing these papers makes them available to the scientific, academic, and professional communities, and all others who need information about this major structural feature of our state. The San Gregorio–Hosgri fault zone has become an increasingly important feature with the advent of coastal zone development in this region of California. Planned power plant sitings and other major facility construction plans depend upon thorough evaluations of this zone.

This group of six papers was compiled and edited by the cochairmen of the GSA symposium: Eli A. Silver and William R. Normark. Their knowledge, skill, and effort in putting this report together is greatly appreciated.

Robert Streitz
Publications Officer

THE SAN GREGORIO–HOSGRI FAULT ZONE: AN OVERVIEW

By Eli A. Silver*

The San Gregorio–Hosgri fault zone is part of the larger San Andreas fault system in California that forms the major locus of shear due to movement between the Pacific and North American plates. An enormous amount of effort has been and is presently being devoted to study of the San Andreas fault itself, and in recent years detailed quantitative knowledge of offset history, seismicity, and present–day movement has increased dramatically (e.g. Kovach and Nur, 1973; Crowell, 1975; Dickinson and Grantz, 1968).

The extent of our knowledge of other faults of the San Andreas system is much less complete; due, in part, to the lower frequency of great earthquakes and smaller offset on subsidiary faults (and therefore, perhaps, lesser interest in these faults). Another reason may be the location of some of the subsidiary faults. The San Gregorio–Hosgri fault zone is located along the coastline south of San Francisco for a length of nearly 400 km, and much of it lies just offshore where it is difficult to study. Major outstanding problems of this fault zone include the details of fault location, continuity between the San Gregorio and Hosgri fault segments, offset history on each segment, evidence for Holocene movements, and seismicity. These problems have importance both for their tectonic implications and their bearing on analysis of seismic hazard for coastal development and power–plant siting.

The papers in this volume were presented as part of a symposium on the San Gregorio–Hosgri fault zone at the Cordilleran section meeting of the Geological Society of America in Sacramento in April 1977. Not all papers presented at the symposium are reproduced here, but those that are give a good overview of the present state of knowledge of this fault zone.

Clark and Brabb discuss the detailed stratigraphy on either side of the San Gregorio fault in its type area. Their careful observations of fundamental stratigraphic differences imply significant differences in sedimentation and tectonic history on either side of the fault. Graham and Dickinson use this and other regional data to infer up to 115 km of right–lateral offset on the fault since Miocene time. This figure is larger than an earlier suggestion of 80 to 90 km (Silver, 1974) based on offset basement terranes using offshore geophysical control. An estimate of 80 to 100 km of post Miocene right–lateral offset on the Hosgri fault (Hall, 1975) ties rather nicely with the above estimates for the San Gregorio segment, but the Hosgri estimate has been questioned (Hamilton and Willingham, 1977). Hall (this volume) briefly addresses these questions and proposes a pull–apart origin for the Santa Maria basin onshore.

The question of continuity of the San Gregorio–Hosgri fault zone focuses on four problem areas: Point Sur, Cape San Martin, San Simeon, and south of Point Sal (figure 1). The Point Sur region is discussed in detail by Graham and Dickinson. Their interpretation that the San Gregorio probably connects with the Sur fault is supported by detailed gravity studies (Woodson, 1973) and argues against a previous suggestion that the main San Gregorio fault trace turns inland south of Monterey to join the Palo Colorado fault (Greene and others, 1973).

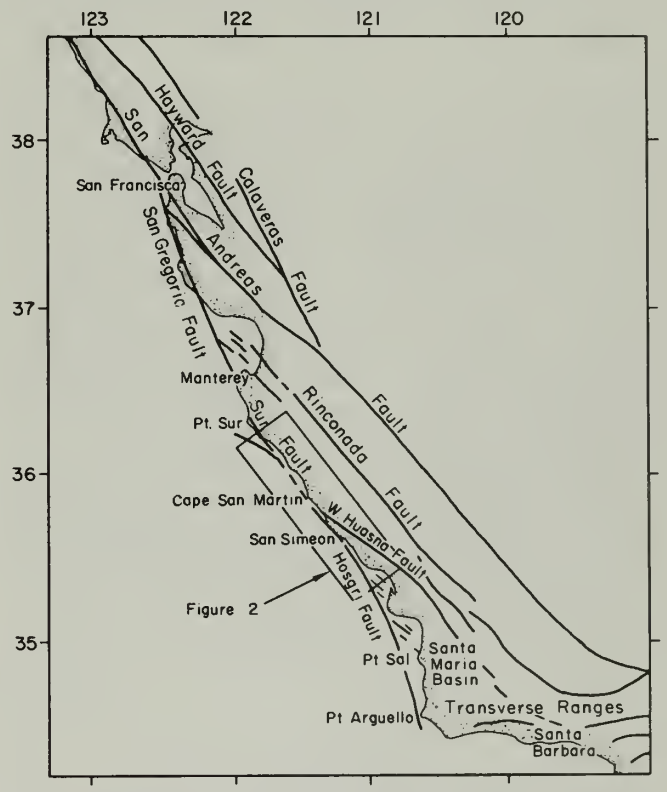

FIGURE 1. Map of central California coast showing geographic locations and faults cited in text and location of Figure 2.

Hall (1975) first suggested that the San Simeon fault is part of the Hosgri fault zone (figure 2). The detailed connection between the Hosgri and San Simeon faults has not been established and some maps show an *en echelon* offset between these faults (Hall, 1975; McCulloch and others, 1977). The San Simeon (Hosgri) segment trends offshore to the north toward Cape San Martin (figure 2). Recently acquired aeromagnetic data (U.S. Geological Survey and California Division of Mines and Geology, unpublished data) reveal a high amplitude anomaly trending northwest across Cape San Martin and seem to require the Hosgri–San Simeon fault either to bend around the anomaly (figure 2) or to step 4 km inland to a fault bounding the east side of the anomaly. If the fault bends around this anomaly it could join a major offshore fault north of Cape San Martin (McCulloch and others, 1977) that trends toward the Sur fault (figure 2). McCulloch and others (1977, figure 2) show a northwest–

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FIGURE 2. Detailed aeromagnetic map of central California coast between Point Sur and San Simeon. Flight lines had 1 mile spacing, flown normal to the coast.

trending fault west of Point Sur (figure 1) which they extend southeastward to the coast, cutting across and separating the Hosgri and Sur faults. This interpretation would imply a definite lack of continuity between the San Gregorio and Hosgri faults in this area. However, their northwest-trending fault must cross a high-amplitude magnetic anomaly that lies parallel to the coast (anomaly bounded by -1.5×10^2 nT contour in figure 2) and this anomaly shows no evidence of a cross-cutting structure. The anomaly also trends parallel to the Sur and Hosgri faults and may be caused by serpentine intrusions along the fault. Structural relations in this near-shore area are obscured by surface slumping (McCulloch and others, 1977, figure 2), and I conclude that the bulk of evidence at present favors, or at least allows, continuity between the Sur and Hosgri faults.

The southern extension of the Hosgri is also in dispute. McCulloch and others (1977) map the fault south of Pt. Arguello, but Hamilton and Willingham (1977), using much the same data, map it no farther south than offshore Point Sal. Either version raises geometrical problems of ending a fault with approximately 100 km of late Cenozoic lateral offset. Various solutions to this problem have been proposed in oral communications, including a bend of the fault into the Transverse Ranges, where the motion would be taken up in compression (D. McCulloch, oral communication, 1977; Hamilton and Willingham, 1977) or an offset of the fault by east-trending faults in the Santa Barbara region (J. Crouch, oral communication, 1976). Satisfactory field documentation, however, has not been reported and this remains an outstanding structural problem.

Holocene movements are well documented for the San Gregorio fault (Weber and Lajoie, 1977; Coppersmith and Griggs, this volume), and studies of seismicity confirm the present-day activity on both the Hosgri and San Gregorio segments (Gawthrop, 1975 and this volume). This information is critical to any planned development along the central California coast because the San Gregorio–Hosgri is very nearly a coastline fault over most of its length.

The San Gregorio–Hosgri appears to be the largest of the subsidiary faults within the San Andreas system, both in length and offset. Other faults, such as the Hayward–Calaveras and Rinconada, have lesser documented offset but also play an important role in the tectonic development of the California Coast Ranges and are deserving of intensive study.

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STRATIGRAPHIC CONTRASTS ACROSS THE SAN GREGORIO FAULT, SANTA CRUZ MOUNTAINS, WEST CENTRAL CALIFORNIA

By Joseph C. Clark[1] and Earl E. Brabb[2]

Abstract

The anshare trace af the San Gregario foult extends fram caastal expasures east af Aña Nuevo Point narthwestword for 27 km (16 mi) ta the caost near San Gregaria. This foult hos juxtopased two majar tectanic blacks with morkedly different strotigrophic sequences.

In the Pigeon Paint black sauthwest af the Son Gregario foult, parphyritic silicic rocks moy form part af the basement; they are averlain by at leost 2,600 m (8,500 ft) of clastic strato af Lote Cretaceaus age. Cretaceous strata ore nat present in the Lo Handa and Ben Lamand blacks nartheast of the fault where mare than 10,000 m (33,000 ft) af Paleocene to Pliacene racks rest on a pre-Tertiary granitic basement. Paleacene ond Eocene racks are nat present in the Pigeon Paint block. Oligocene (Zemorrian) and middle Miacene (Relizian and Luision) strota accur in bath tectonic blacks, but they differ in lithalogy, fauno, and bathymetry an oppasite sides. A thick upper Miacene ta lower Pliacene mudstone sectian in the La Handa and Ben Lamand blacks is missing west af the fault.

INTRODUCTION

The regional structure of the Santa Cruz Mountains has long been considered as a number of independent fault blocks with different stratigraphic and structural histories (Clark, 1930). The greatest differences are across the San Andreas fault and its ancestral branch, the Pilarcitos fault. The Franciscan assemblage of Jurassic and Cretaceous ages, and its associated mafic and ultramafic basement rocks on the northeast side, are thought to have been deposited in a deep ocean environment. On the southwest side, Cretaceous and Tertiary sedimentary and volcanic rocks were deposited on a continental block of granitic rocks, generally referred to as the Salinian block. Hill and Dibblee (1953) indicated that the Salinian block may be offset laterally by the San Andreas fault from the southern part of the Sierra Nevada.

Within the Salinian block, we have subdivided the Santa Cruz Mountains into three smaller blocks (figure 1). The La Honda and Ben Lomond blocks east of the San Gregorio fault have granitic basement rocks on which were deposited at least 10,000 m (33,000 ft) of Cenozoic clastic sedimentary and volcanic rocks. The Pigeon Point block west of the San Gregorio fault, by contrast, has at least 2,600 m (8,500 ft) of Cretaceous and only 1,200 m (3,900 ft) of Cenozoic sedimentary rocks. These rocks may have been deposited locally on rhyolitic basement.

Hill and Dibblee (1953, plate 1) suggested that the San Gregorio fault might have substantial strike–slip displacement. Cummings and others (1962, p. 215), on the other hand, believed that substantial strike separation was unlikely because they could map similar Pliocene rocks on both sides of the fault. Recent mapping in the Santa Cruz Mountains (Brabb, 1970; Clark, 1970) has, however, revealed differences across this fault. The purpose of this paper is to summarize and compare the on–land geologic sections across this fault in the Santa Cruz Mountains.

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GEOLOGIC SECTION NORTHEAST OF THE SAN GREGORIO FAULT

Crystalline Rocks

Crystalline rocks northeast of the San Gregorio fault, best exposed at Ben Lomond Mountain (figure 1), consist of an elongate granitic complex with several large metasedimentary roof pendants (Leo, 1967; Ross and Brabb, 1973). The plutonic rocks range in composition from gabbro to granite, of which hornblende–biotite quartz diorite is dominant and forms about three–quarters of the exposed plutonic complex. The metasedimentary rocks are predominantly pelitic schists and quartzites with minor amounts of marble and calc–silicate rocks.

The crystalline basement surface drops off abruptly southwest of Ben Lomond Mountain. The Shell Davenport core hole no. 1 (figure 1), located less than 1.6 km (1 mi) from quartz–diorite outcrops, reached a depth of 1,260 m (4,110 ft) before penetrating granitic rock. Farther west, but still east of the San Gregorio fault, the Texas Poletti well reached granitic rocks at a depth of 2,800 m (9,140 ft), indicating that the basement descends over 2,750 m (9,000 ft) in 3.6 km (2.3 mi). On a deep penetration seismic profile off the coast, the basement surface appears to dip steeply westward into the offshore continuation of the San Gregorio fault (H.G. Greene, oral communication, 1974).

Sedimentary and Volcanic Rocks

The Tertiary section consists predominantly of marine clastic sedimentary rocks ranging in age from Paleocene to Pliocene and having a composite thickness of more than 10,000 m (33,000 ft) (figure 2). This section is divisible into four major sedimentary rock sequences, each bounded by regional unconformities. Each sequence rests locally on crystalline basement rocks.

Paleocene sequence..—Paleocene rocks consist of erosional remnants of sandstone and siltstone exposed around the granitic cores of Ben Lomond and Montara Mountains. In the Ben Lo-

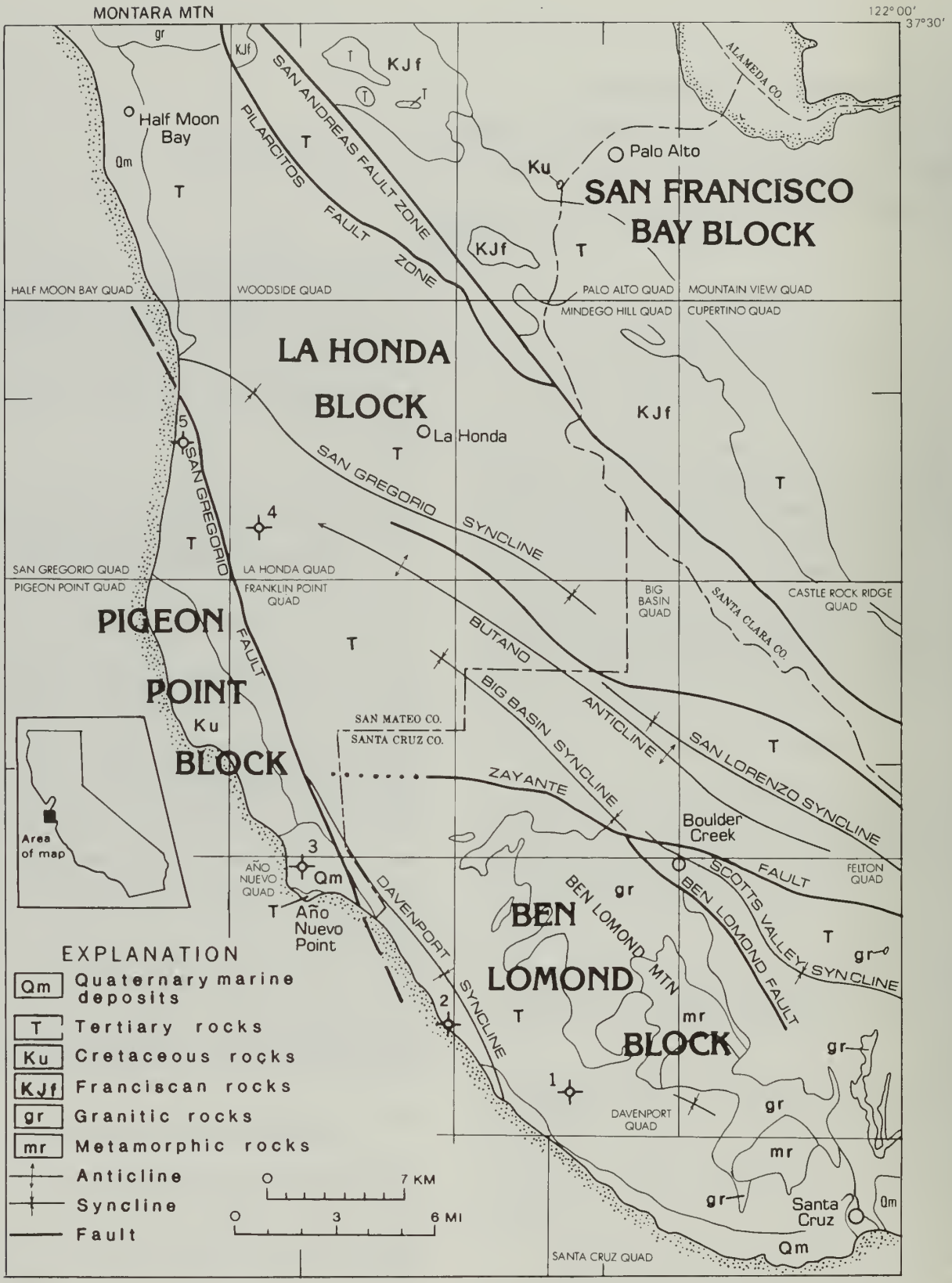

FIGURE 1. Generalized geologic map of the narthern and central Santa Cruz Mauntains. Oil wells mentianed in the text include: (1) Shell Davenport care hale 1, T. D. 4315 feet; (2) Texas Paletti 1, T. D. 9197 feet; (3) Richfield Steele care hale 1, T. D. 2675 feet; (4) Texas Steele 1, T. D. 8025 feet; and (5) Walker–Manyier Caughey 1, T. D. 3338 feet.

mond Mountain area, the Locatelli Formation of Cummings and others (1962) comprises at least 270 m (900 ft) of siltstone beds deposited in bathyal depths and open–ocean conditions and, locally, a basal sandstone of shallow marine origin. The unnamed rocks around Montara Mountain are considerably different in lithology—they are mostly rhythmically interbedded sandstone and shale that compare with some of the interchannel deposits of deep–sea fans described by Nelson and Nilsen (1974). The map and sections of Darrow (1963, plates 1 and 2) indicate that the sequence at Montara Mountain is at least 600 m (2,000 ft) thick.

Eocene to lower Miocene sequence.—The Eocene to lower Miocene sequence is more than 4,500 m (15,000 ft) thick. It is most extensively developed in the La Honda block but also crops out locally in the Ben Lomond block. This sequence includes the Butano Sandstone, the San Lorenzo Formation, the Zayante Sandstone, the Vaqueros Sandstone, the Mindego Basalt, and the Lambert Shale (figure 2). The lithology, stratigraphic relations, fossils, paleoecology, and age of these formations are described in some detail by Cummings and others (1962), Clark (1968), and Nilsen and Simoni (1973).

The Butano Sandstone is a deep–sea fan deposit derived from a potash–rich granitic terrain south and possibly west of the La Honda and Ben Lomond blocks in what is now the Pacific Ocean. Nilsen and Clarke (1975, figure 7) envision the source area as an island in the continental borderland. The overlying Twobar Shale Member of the San Lorenzo Formation indicates that this source area was substantially reduced in elevation by late Eocene (late Narizian) time, and that deposition in the La Honda block was in a slowly subsiding basin at bathyal or abyssal depths and with open connection to the ocean. The Rices Mudstone Member of the San Lorenzo Formation, like the Twobar, shoals and is sandier in a westerly direction within the La Honda block. Conversely, the deepest part of the basin is truncated to the east by the San Andreas fault.

The Zayante Sandstone is a local, nonmarine facies associated with uplift of the Ben Lomond block during the Oligocene (Clark and Rietman, 1973). Eruption of submarine pillow basalt in the La Honda area interrupted deposition of the Vaqueros Sandstone and Lambert Shale in deeper parts of the La Honda block.

Middle Miocene sequence.—The middle Miocene sequence consists of a widely transgressive basal sandstone unit, the Lompico Sandstone of Clark (1966), and an overlying organic mudstone unit, the Monterey Formation. This marine sequence is more than 900 m (3,000 ft) thick along the Scotts Valley syncline and it is discontinuously distributed in the La Honda and Ben Lomond blocks.

The Lompico Sandstone rests nonconformably upon the crystalline basement and unconformably upon the more strongly deformed beds of the Eocene to lower Miocene sequence. These sandstone beds of late Relizian to early Luisian age were laid down in a near–shore shallow–marine environment.

Conformable upon the Lompico Sandstone are the semi–siliceous organic mudstone beds of the Monterey Formation. Where the basal sandstone beds are locally absent in the Mindego Hill quadrangle, glauconitic siltstone beds of the Monterey are unconformable on older rocks (Cummings and others, 1962, p. 194). The mudstone beds of the Monterey Formation yield foraminifers diagnostic of late Relizian to Luisian age and were generally deposited at neritic depths.

On the southwest slope of Ben Lomond Mountain, the Monterey Formation is also conformable above the Lompico Sandstone, but there it is typically medium–bedded sandy siltstone with very thick arkosic sandstone interbeds. Shallow–water conditions probably persisted in that area throughout deposition of the middle Miocene sequence, for this section of the Monterey Formation yields only shallow–water foraminiferal faunas that include such characteristic shallow taxa as *Ammonia beccarii, Buccella oregonensis, Buliminella elegantissima,* and *Elphidium hughesi.*

Upper Miocene to Pliocene sequence.—The upper Miocene to Pliocene sequence consists of a shallow–water, transgressive sandstone unit, the Santa Margarita Sandstone; a deeper water, siliceous organic mudstone unit, the Santa Cruz Mudstone of Clark (1966); and a shallower water unit, the Purisima Formation. It has a composite thickness of about 4,550 m (14,900 ft). This sequence rests unconformably on all older rocks and is widely exposed in both the Ben Lomond and La Honda blocks.

The Santa Margarita Sandstone is most extensively developed along the Scotts Valley syncline, where it reaches its maximum thickness of 130 m (430 ft). On the southwestern slope of Ben Lomond Mountain, this sandstone unit crops out discontinuously beneath the Santa Cruz Mudstone, where it is locally bituminous.

The Santa Cruz Mudstone is extensively exposed along the coastal west–central Santa Cruz Mountains from the southern part of the La Honda quadrangle southeastward to Santa Cruz. It thickens westward from about 140 m (450 ft) near the western limit of Santa Cruz to more than 385 m (1,260 ft) in the Shell Davenport core hole no. 1 and more than 2,700 m (8,850 ft) in the Texas Poletti well (figure 1). This thickness continues northward into the La Honda quadrangle where Touring (1959, plate 12) indicates that the Texas Steele no. 1 well, located about 1 km (½ mi) east of the San Gregorio fault, penetrated about 2,400 m (8,000 ft) of this mudstone (his Monterey Formation) but did not reach its base.

The Purisima Formation is most extensively developed in the northern part of the La Honda block where it is as much as 1,725 m (5,650 ft) thick and has been subdivided by Cummings and others (1962, p. 197–210) into five members, which are, from youngest to oldest:

Tunitas Sandstone Member
Lobitos Mudstone Member
San Gregorio Sandstone Member
Pomponio Mudstone and Siltstone Member
Tahana Sandstone and Siltstone Member

The Purisima Formation rests conformably on the Santa Cruz Mudstone at some localities but in other areas it rests unconformably on the Monterey, Mindego, San Lorenzo, and other formations.

GEOLOGIC SECTION SOUTHWEST OF THE SAN GREGORIO FAULT

Crystalline Rocks

Porphyritic volcanic rocks that crop out south of Pescadero Road near the boundary of the San Gregorio and Pigeon Point quadrangles may form part of the basement complex west of this

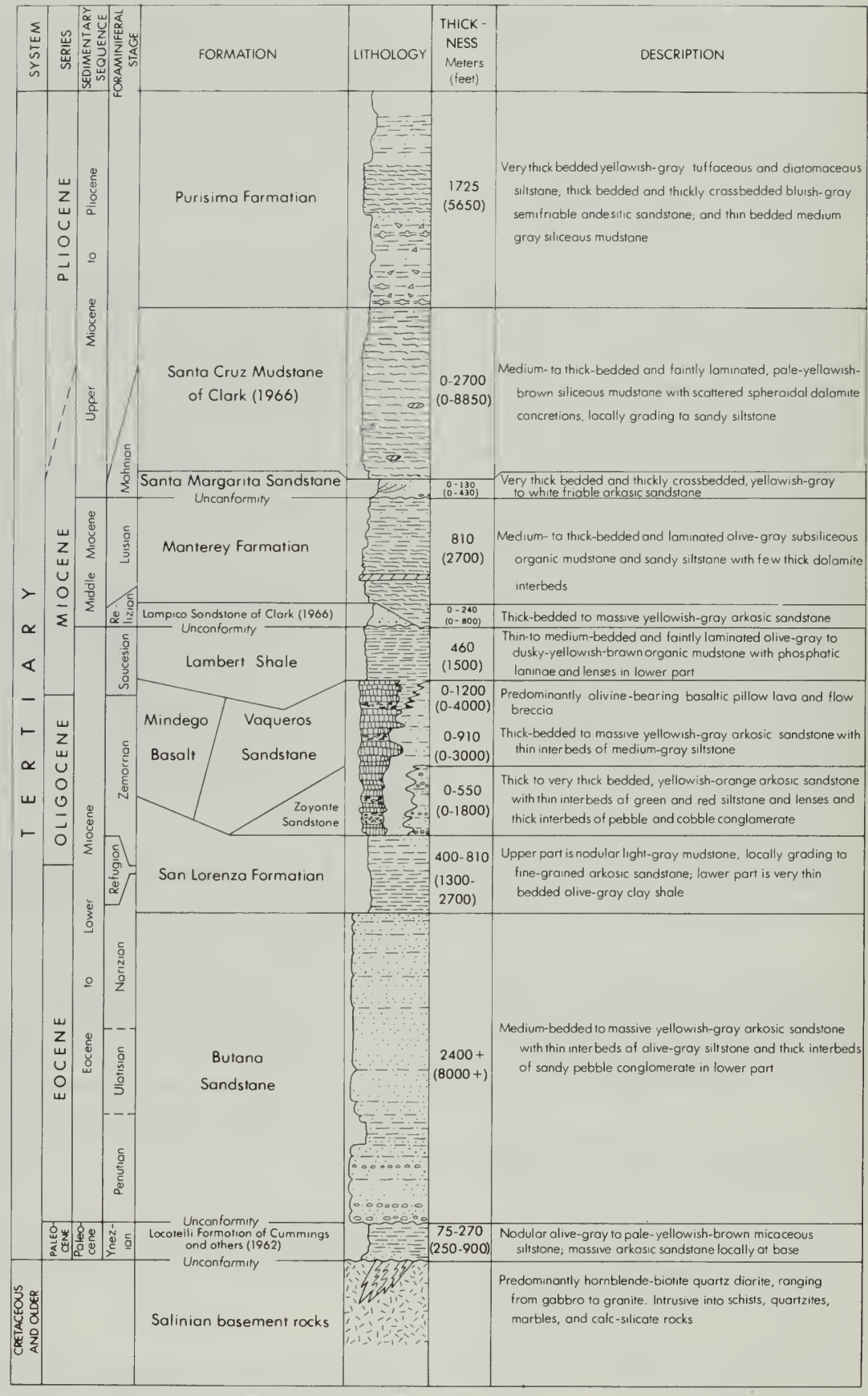
SYSTEM
SERIES
SEDIMENTARY SEQUENCE
FORAMINIFERAL STAGE
FORMATION
LITHOLOGY
THICK-NESS Meters (feet)
DESCRIPTION
TERTIARY
PLIOCENE
Pliocene to Upper Miocene
Mohnian
Purisima Formation
1725 (5650)
Very thick bedded yellowish-gray tuffaceous and diatomaceous siltstone, thick bedded and thickly crossbedded blurish-gray semifriable andesitic sandstone, and thin bedded medium gray siliceous mudstone
Santa Cruz Mudstone of Clark (1966)
0-2700 (0-8850)
Medium- to thick-bedded and faintly laminated, pale-yellowish-brown siliceous mudstone with scattered spheroidal dolomite concretions, locally grading to sandy siltstone
Santa Margarita Sandstone
0-130 (0-430)
Very thick bedded and thickly crossbedded, yellowish-gray to white friable arkosic sandstone
Unconformity
MIOCENE
Middle Miocene
Luisian
Manterey Formation
810 (2700)
Medium- to thick-bedded and laminated olive-gray subsiliceous organic mudstone and sandy siltstone with few thick dolomite interbeds
Relizian
Lompico Sandstone of Clark (1966)
0-240 (0-800)
Thick-bedded to massive yellowish-gray arkosic sandstone
Unconformity
Saucesian
Lambert Shale
460 (1500)
Thin- to medium-bedded and faintly laminated olive-gray to dusky-yellowish-brown organic mudstone with phosphatic laminae and lenses in lower part
Zemorrian
Mindego Basalt
Vaqueros Sandstone
0-1200 (0-4000)
Predominantly olivine-bearing basaltic pillow lava and flow breccia
0-910 (0-3000)
Thick-bedded to massive yellowish-gray arkosic sandstone with thin interbeds of medium-gray siltstone
Zoyonte Sandstone
0-550 (0-1800)
Thick to very thick bedded, yellowish-orange arkosic sandstone with thin interbeds of green and red siltstone and lenses and thick interbeds of pebble and cobble conglomerate
OLIGOCENE
Lower Miocene
Refugian
San Lorenza Formation
400-810 (1300-2700)
Upper part is nodular light-gray mudstone, locally grading to fine-grained arkosic sandstone; lower part is very thin bedded olive-gray clay shale
EOCENE
Eocene to Lower Miocene
Narizian
Ulatisian
Penutian
Butana Sandstone
2400+ (8000+)
Medium-bedded to massive yellowish-gray arkosic sandstone with thin interbeds of olive-gray siltstone and thick interbeds of sandy pebble conglomerate in lower part
Unconformity
PALEOCENE
Paleocene
Ynezian
Locatelli Formation of Cummings and others (1962)
75-270 (250-900)
Nodular olive-gray to pale-yellowish-brown micaceous siltstone; massive arkosic sandstone locally at base
Unconformity
CRETACEOUS AND OLDER
Salinian basement rocks
Predominantly hornblende-biotite quartz diorite, ranging from gabbro to granite. Intrusive into schists, quartzites, marbles, and calc-silicate rocks

FIGURE 2. Composite geologic section northeast of the San Gregorio fault.

fault. These volcanic rocks are finely brecciated and contain quartz, plagioclase (An_{20-28}), and orthoclase(?) phenocrysts, locally up to 3.5 mm in diameter, in a silicic matrix. The matrix includes devitrified glass and consists of relict microspherulites and interstitial quartz, possibly some potassium feldspar, clay minerals, including chlorite, and some microgranular hematite.

The quartz phenocrysts, plagioclase composition, low percentage of ferromagnesian minerals, and abundant quartz in the groundmass suggest that the original rock was highly silicic and probably a rhyolite. Metamorphism of the rock is limited to dynamic distortion of the phenocrysts, granulation along narrow bands, and perhaps low–rank thermal metamorphism of clay devitrification products to chlorite.

Although these distinctive volcanic rocks are shown as "Miocene basalt" on the San Francisco sheet of the Geologic Map of California (Jennings and Burnett, 1961), they differ lithologically from any of the exposed Tertiary volcanic rocks in the Santa Cruz Mountains. The contact between these porphyritic rocks and the Pigeon Point Formation that crops out to the west and to the south is not exposed, but structural attitudes in the Pigeon Point Formation suggest that the volcanic rocks underlie this formation. In addition, abundant dark silicic porphyry clasts in conglomeratic beds of the Pigeon Point Formation strongly resemble these volcanic rocks. Thus, the porphyritic rhyolite may form part of the basement west of the San Gregorio fault and is of Cretaceous or older age.

Sedimentary and Volcanic Rocks

Sedimentary strata exposed southwest of the San Gregorio fault are of Mesozoic and Cenozoic age (figure 3). The Mesozoic section consists of more than 2,600 m (8,500 ft) of marine clastic sedimentary rocks, the Pigeon Point Formation of Late Cretaceous age. This formation crops out along the coast and has been penetrated in the subsurface of the Año Nuevo quadrangle. Unconformable upon, and locally faulted against, the Pigeon Point Formation are approximately 1,200 m (3,900 ft) of clastic sedimentary and volcanic rocks that range in age from Oligocene (Zemorrian) to Holocene. This Cenozoic section includes the Vaqueros(?), Monterey, and Purisima Formations, which are complexly folded and faulted in exposures north and east of Año Nuevo Point.

Pigeon Point Formation.—The Pigeon Point Formation (Hall and others, 1959) comprises 2,600 m (8,500 ft) of Cretaceous strata that are discontinuously exposed for 17 km along the coast from Pescadero Beach in the southern part of the San Gregorio quadrangle southward to midway between Franklin Point and Año Nuevo Point in the Franklin Point quadrangle (figure 1). These strata are extensively folded and faulted. They consist of a heterogeneous sequence of interbedded sandstone, mudstone, and conglomerate which displays a variety of sedimentary structures. Lowe (1972) informally subdivided it into two parts: a lower 1,800 m (5,900 ft) of thick units of interbedded sandstone and mudstone, and an upper 900 m (3,000 ft) of bedded conglomerate; of interbedded conglomerate, pebbly mudstone, and coarse–grained sandstone; and of cross–bedded, fine–grained sandstone. He interprets the lower part as having been deposited in part by turbidity currents upon the continental slope or upon the uppermost continental rise, and the upper part as representing submarine canyon or slope fill and shallow shelf sediments.

Pigeon Point Formation sand grains are angular to subangular and are composed predominantly of quartz (45 to 80 percent), feldspar (20 to 50 percent), and lithic fragments (10 to 30 percent), with volcanic and granitic clasts more abundant than metamorphic and sedimentary types (Tyler, 1972, page 544). Conglomerates consist mainly of well–rounded pebbles and cobbles of silicic volcanic, plutonic (mostly quartz diorite), and metasedimentary rocks. Thus, the sediments were derived largely from the crystalline rocks of the Salinian block and from a silicic volcanic terrane. The porphyritic rhyolite that apparently underlies the Pigeon Point Formation west of the San Gregorio fault may represent a part of this volcanic terrane. The relative abundance of the volcanic clasts and the postulated northeast–to–southwest paleocurrent movement for the sediments of the Pigeon Point Formation (Tyler, 1972, p. 553) are consistent with this source interpretation.

The base of the Pigeon Point Formation is not exposed. At Pescadero Beach in the southernmost part of the San Gregorio quadrangle (figure 1), this formation is overlain with marked angular discordance by conglomerate and sandstone beds of the Vaqueros(?) Formation. South of and inland from Pescadero Beach, the Pigeon Point Formation is overlain unconformably by the Purisima Formation. In sea–cliff exposures 2.2 km (1.4 mi) north of Año Nuevo Point in the Franklin Point quadrangle, very thick sandstone beds of the Purisima Formation rest with clear angular discordance upon the more steeply dipping beds of the Pigeon Point Formation.

Fossils listed by Branner and others (1909) and by Hall and others (1959) are diagnostic of Campanian and probably Maestrichtian age. Foraminifera identified by R. L. Pierce (written communication, 1963) from the Richfield Steele core hole near Año Nuevo Point (figure 1) range in age from "probably Goudkoff's D–1 zone" (Maestrichtian) downward to "Goudkoff's F–2 and(or)G–1 zone"(Campanian, Santonian, and (or) Coniacian). The upper and lower age limits of the Pigeon Point Formation have not been determined.

Vaqueros(?) Formation.—Strata referred to as the Vaqueros(?) Formation by Hall and others (1959, figure 2) crop out at Pescadero Beach in the southern part of the San Gregorio quadrangle and along the coast north and east of Año Nuevo Point. The name "Vaqueros" is probably inappropriate for these strata but is provisionally retained until the unit can be properly defined. At Pescadero Beach, this formation consists of as much as 135 m (450 ft) of sandstone and calcarenite. The basal beds rest with marked angular discordance on steeply dipping beds of the Pigeon Point Formation. The lower part of the section consists of thick– to very thick–bedded, locally cross–bedded, coarse– to medium–grained arkosic sandstone. Medium conglomerate interbeds in the basal 3 m (10 ft) of this section contain well–rounded, dark silicic porphyry and light–colored quartzite pebbles and cobbles, and fewer granitic cobbles and boulders. All the beds appear to have been deposited in shallow water near the strand line.

Overlying these sandstone beds are thick, hard, resistant beds of calcarenite. The calcarenite consists of recrystallized calcareous detritus and cement with detrital quartz, plagioclase feldspar, and altered volcanic rock fragments. The calcarenite beds, in turn, are overlain by fine–grained glauconitic sandstone.

This Vaqueros(?) section at Pescadero Beach has yielded *Macrochlamis magnolia* and has been assigned a probable Oligocene (Zemorrian) age by Cummings and others (1962, p. 183; their Mindego Formation).

To the north along Pescadero Beach, the glauconitic sandstone beds are overlain by volcanic breccia. The breccia consists

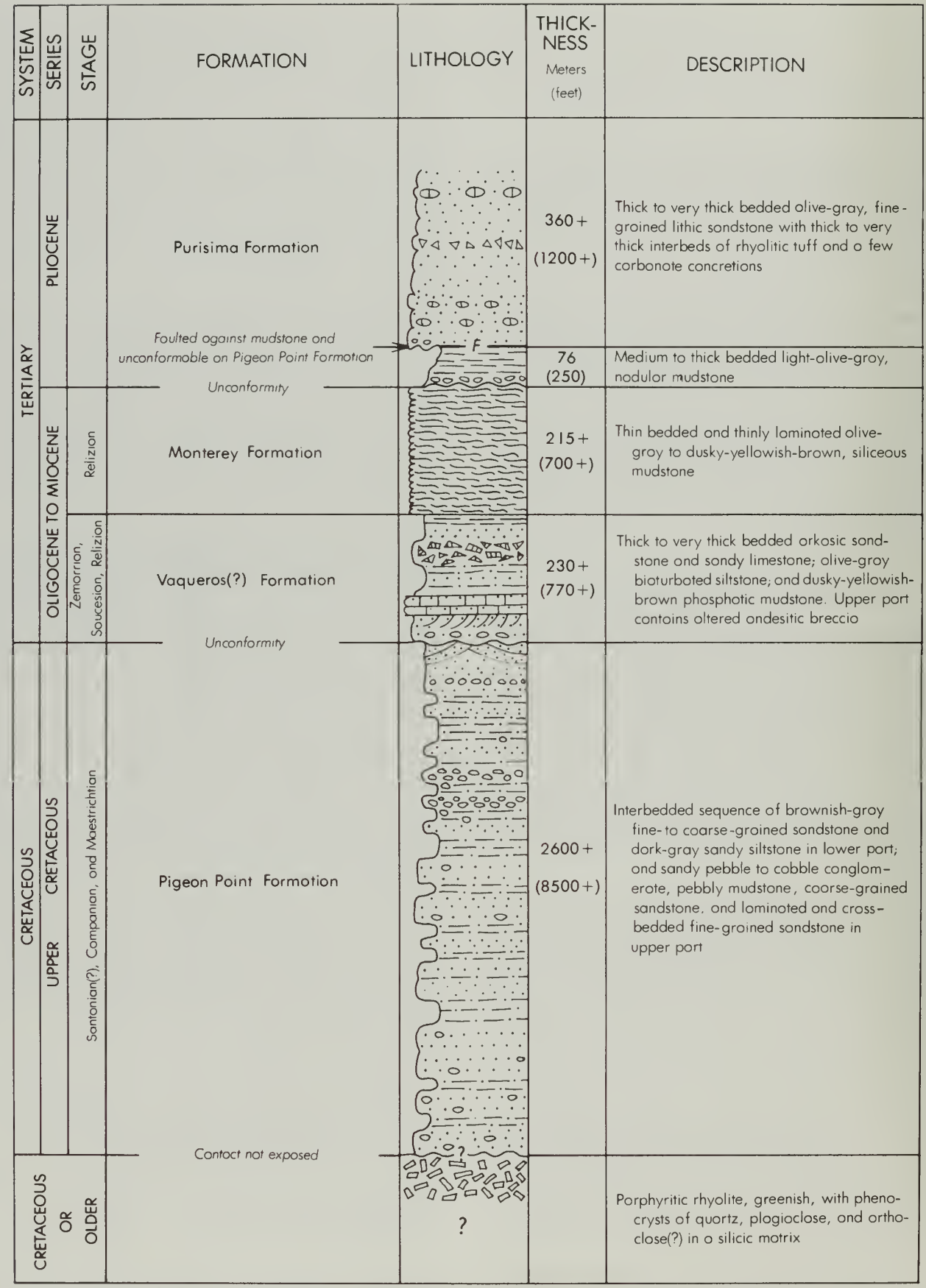
SYSTEM
SERIES
STAGE
FORMATION
LITHOLOGY
THICK-NESS Meters (feet)
DESCRIPTION
TERTIARY
PLIOCENE
Purisima Formation
360+ (1200+)
Thick to very thick bedded olive-gray, fine-grained lithic sandstone with thick to very thick interbeds of rhyolitic tuff and a few carbonate concretions
Faulted against mudstone and unconformable on Pigeon Point Formation
F
76 (250)
Medium to thick bedded light-olive-gray, nodular mudstone
Unconformity
OLIGOCENE TO MIOCENE
Relizian
Monterey Formation
215+ (700+)
Thin bedded and thinly laminated olive-gray to dusky-yellowish-brown, siliceous mudstone
Zemorrian, Soquesian, Relizian
Vaqueros(?) Formation
230+ (770+)
Thick to very thick bedded arkosic sandstone and sandy limestone; olive-gray bioturbated siltstone; and dusky-yellowish-brown phosphatic mudstone. Upper part contains altered andesitic breccia
Unconformity
CRETACEOUS
UPPER CRETACEOUS
Santonian(?), Campanian, and Maestrichtian
Pigeon Point Formation
2600+ (8500+)
Interbedded sequence of brownish-gray fine- to coarse-grained sandstone and dark-gray sandy siltstone in lower part; and sandy pebble to cobble conglomerate, pebbly mudstone, coarse-grained sandstone, and laminated and cross-bedded fine-grained sandstone in upper part
Contact not exposed
?
CRETACEOUS OR OLDER
?
Porphyritic rhyolite, greenish, with phenocrysts of quartz, plagioclase, and orthoclase(?) in a silicic matrix

FIGURE 3. Composite geologic section southwest of the San Gregorio fault.

predominantly of angular boulders and cobbles of altered andesite and locally includes internally deformed sandstone and siltstone boulders. These clasts are set in a matrix of calcareous sandstone and calcarenite.

About 1.6 km (1 mi) north of Año Nuevo Point within the Franklin Point quadrangle, 85 m (280 ft) of the Vaqueros(?) Formation are exposed at low tide below the beach. The formation at this locality consists predominantly of olive–gray to dusky–yellowish–brown bioturbated siltstone; bedding is defined by a few thick, graded, fine– to very fine–grained arkosic sandstone interbeds. Some of the siltstone contains thin phosphatic lenses, and it is cut locally by numerous thin sandstone dikes. These beds are folded into a syncline, the northern limb of which becomes vertical and is locally overturned.

Locally some of the siltstone beds contain abundant calcareous foraminifers characteristic of lower bathyal depths. *Siphogenerina nodifera* is diagnostic of Zemorrian (Oligocene) age, and the joint occurrence of *S. nodifera* with *S. mayi* in the upper part of this section is diagnostic of late Zemorrian age. The uppermost part of this section may range into Saucesian(early Miocene) age, for the stratigraphically highest faunal assemblage is either late Zemorrian or early Saucesian.

About 370 m (1,200 ft) east of Año Nuevo Point, the Vaqueros(?) Formation is exposed along the beach and sea cliffs near the axis of an anticline, the central part of which is occupied by volcanic breccia. The formation in that area consists of laminated, dusky–yellowish–brown phosphatic mudstone interbeds with medium– to fine–grained, glauconite–bearing arkosic sandstone. East of a volcanic headland, where about 12.5 m (41 ft) of the Vaqueros(?) Formation are exposed in the sea cliffs, sandstone predominates in the lower part of the section, whereas the upper part consists mainly of contorted and sheared mudstone. West of the volcanic outcrops, where about 13 m (45 ft) of this formation are discontinuously exposed below the beach, the lower part of the Vaqueros(?) includes dark–yellowish–brown, burrowed siltstone beds that resemble those exposed to the north in the Franklin Point quadrangle.

The volcanic breccia is highly altered and cut by siliceous and dolomitic veins. One rock is fine–grained and microporphyritic, with microphenocrysts of plagioclase (labradorite) up to 1.4 mm long and ghosts of pyroxene that range from 0.80 mm to 1.2 mm altered to clay and calcite. The groundmass consists largely of a felted mass of skeletal plagioclase microlites, and of clay alteration products. Quartz occurs locally between feldspars and in interstices. Calcite is common and is probably a replacement and alteration product; locally it fills amygdules. This rock is probably a tholeiitic basalt. Other volcanic blocks are more felsic and are probably andesites. This volcanic breccia appears similar, both petrographically and in outcrop, to that exposed at Pescadero Beach to the north.

On the east flank of the anticline, sandstone beds of the Vaqueros(?) Formation locally appear to rest upon the volcanic breccia. Two large blocks of mudstone are included in the breccia just west of this contact.

Mudstone beds within the Vaqueros(?) section east of Año Nuevo Point yield deep–water calcareous foraminifers diagnostic of Saucesian and Relizian ages. The stratigraphically lowest faunas are from the discontinuous intertidal exposures just west of the volcanic breccia and include *Bulimina alligata, Cibicides dohertyi, C. floridanus, Dentalina quadrulata, Siphogenerina multicostata, S. transversa, and Uvigerinella obesa impolita,* which together are diagnostic of Saucesian (probably early Saucesian) age. The sheared mudstone beds from the upper part of the section east of the volcanic breccia yield foraminifers diagnostic of Relizian age. *Siphogenerina* cf. *S. hughesi* from the lower part of this sheared section is suggestive of early Relizian age. Higher in the sheared section, taxa characteristic of the pseudosaucesian facies of Beck (1952) are associated with middle Miocene (probably Relizian) species. The foraminiferal dating thus suggests that the Vaqueros(?) Formation that crops out to the north of Año Nuevo Point is older than most, if not all, of the section to the east of the point.

The base of the Vaqueros(?) Formation is not exposed in the vicinity of Año Nuevo Point. The mudstone beds of the Vaqueros(?) Formation are faulted against siliceous beds of the Monterey Formation on the east flank of the anticline, whereas to the west the Vaqueros(?)–Monterey contact is concordant and appears to be gradational.

Monterey Formation.—The Monterey Formation is well exposed in the sea cliffs north and east of Año Nuevo Point and on Año Nuevo Island. This formation there consists predominantly of thin–bedded and thinly laminated, olive–gray to dusky yellowish–brown siliceous mudstone. The siliceous beds are brittle and fractured and locally alternate with thin beds of less siliceous mudstone and slightly glauconitic siltstone.

More than 215 m (700 ft) of the Monterey Formation are gently folded between Año Nuevo Island and the contact with the underlying Vaqueros(?) Formation to the east.

The Monterey Formation locally yields foraminifers that are characteristic of the upper bathyal biofacies (300 ± 185 m – 1,000 ± 600 ft) of Bandy and Arnal (1969). The joint occurrence of *Bolivina advena* var. *striatella, Valvulineria* cf. *V. californica* var. *obesa,* and of *V.* cf. *V. depressa* is diagnostic of late Relizian to early Luisian age, middle Miocene of California usage. *Nonion incisum* suggests that at least the lower part of this section is restricted to the upper Relizian.

The contact with the subjacent Vaqueros(?) Formation appears to be gradational, whereas the contact with the superjacent Purisima Formation is clearly unconformable. This latter contact is well exposed in the sea cliffs about 640 m (2,100 ft) east of Año Nuevo Point, where a 1.2–to–1.5 m (4–to–5 ft) – thick basal conglomerate bed of the Purisima Formation composed largely of siliceous Monterey cobbles rests with slight angular discordance upon the siliceous beds of the Monterey.

Although the Monterey Formation does not crop out in the Pigeon Point block north of the Año Nuevo quadrangle, a thick section may be present in the subsurface to the north, for Touring (1959, plate 11) reports that the Walker and Monyier Caughey no. 1 well (figure 1) penetrated more than 600 m (2,000 ft) of this formation beneath the Tahana Sandstone and Siltstone Member of the Purisima Formation.

Purisima Formation.—The Purisima Formation is extensively exposed west of the San Gregorio fault, where it consists of several lithologic units that are not seen in depositional contact, and their stratigraphic interrelationship is in doubt.

The largest area of Purisima, assigned to the Tahana Sandstone and Siltstone Member by Cummings and others (1962), extends as a broad band west of the fault from the San Gregorio quadrangle southward through the Franklin Point quadrangle.

The Purisima there is dominantly fine– to medium–grained volcanic arenite with several thick to very thick rhyolitic tuff interbeds. Pebble conglomerate interbeds are locally developed near the base.

This northern Purisima section is more than 360 m (1,200 ft) thick, for the Walker and Monyier Caughey no. 1 well in the northern part of the San Gregorio quadrangle (figure 1) penetrated that much above the Monterey Formation (Touring, 1959, plate 11). In the northeastern part of the Pigeon Point quadrangle, gently dipping beds of this Purisima unit rest unconformably on nearly vertical strata of the Pigeon Point Formation, and to the north along Pescadero Road this unit rests unconformably on the porphyritic rhyolite. Locally, these Purisima beds are overlain unconformably by Pleistocene terrace deposits.

The Purisima Formation also crops out along the sea cliffs north and east of Año Nuevo Point in the Franklin Point and Año Nuevo quadrangles. A mudstone section of the Purisima is exposed only above an isolated beach east of Año Nuevo Point. About 76 m (250 ft) of mudstone crop out there above the unconformable contact with the Monterey Formation to the west and a fault that brings it into contact with Purisima sandstone beds to the east (Clark, 1970).

The lowermost part of this mudstone section is medium to thick bedded, but to the east the mudstone is nodular and highly fractured, and bedding is not apparent. The mudstone contains abundant diatoms, a few fish bone fragments, and a few small pelecypods. A sample from approximately 15 m (50 ft) above the base of this section has yielded a diatom flora diagnostic of early Pliocene age—Zone IX of the North Pacific diatom chronology (J.A. Barron, written communication, 1977).

Farther east of Año Nuevo Point, sandstone beds of the Purisima Formation are discontinuously exposed along the sea cliffs eastward to the San Gregorio fault (Clark, 1970). These beds are folded and extensively faulted, and an unnamed fault about 1.4 km (0.9 mi) east of the point separates two faunally distinct sections of the Purisima. The molluscan fauna from the section west of this fault was believed by Branner and others (1909, p. 6) to be similar to that of the type Purisima to the north. Neither the base nor the top of this section is exposed in the sea cliffs. It probably rests unconformably upon the Pigeon Point Formation because lithologically similar sandstone beds of the Purisima are unconformable upon strata of the Pigeon Point about 2 km (1.2 mi) to the north.

The eastern sandstone section that is truncated by the San Gregorio fault is more fossiliferous. Because Branner and others (1909) believed that the fauna there was younger than typical Purisima and similar to that of the lower part of the type Merced Formation, they incorrectly mapped these eastern beds as "Merced."

From an isolated Purisima sandstone exposure west ot the San Gregorio fault that is about 1 km (½ mi) north of and on strike with this eastern Purisima sea cliff section, the writers collected *Dendraster gibbsi* (Rémond). This echinoid species is reported by Touring (1959, p. 185) to be common in one bed of the upper part of the upper Pliocene San Gregorio Sandstone Member of the Purisima of Cummings and others (1962). The fauna from this eastern sandstone section thus suggests that these beds are, at least in part, of late Pliocene age and may be correlative with the lithologically similar San Gregorio Sandstone Member of the Purisima.

CORRELATIONS ACROSS THE SAN GREGORIO FAULT

The geologic sections juxtaposed by the San Gregorio fault are summarized in Figure 4, and their comparison suggests extensive lateral displacement.

Pre–Tertiary Sections

Typical Salinian basement rocks are not exposed nor have they been reported from the subsurface of the Pigeon Point block. The porphyritic rhyolite that crops out west of the San Gregorio fault may form part of the basement of this block. These distinctive rocks are unlike any of the crystalline rocks of the Salinian block that are exposed in the Santa Cruz Mountains to the east.

Upper Cretaceous strata extensively developed west of the fault are notably absent between the San Gregorio and San Andreas faults. Farther east in the Santa Cruz Mountains, correlative strata do crop out in the San Francisco Bay block east of the San Andreas fault.

Tertiary Sections

The Paleocene beds that occur as scattered erosional remnants on the granitic basement of Ben Lomond and Montara Mountains appear to be missing from the Pigeon Point block. Likewise, the Butano Sandstone, which is widely distributed in the La Honda block and locally preserved in the Ben Lomond block, and the San Lorenzo Formation of the La Honda block are absent to the west of the San Gregorio fault.

Sandstone, calcarenite, siltstone, and phosphatic mudstone beds of Oligocene (Zemorrian) to early Miocene (Saucesian) age that are assigned to the Vaqueros(?) Formation west of the fault are correlative with the Vaqueros Sandstone and the Lambert Shale of the La Honda block. The calcarenite beds of Pescadero Beach are lithologically distinct and unlike any of the correlative beds to the east. The correlative lower Saucesian sections do include lithologically similar phosphatic mudstones. However, the Zemorrian paleogeography of the central Santa Cruz Mountains strongly suggests that the Ben Lomond block was emergent during Zemorrian time, which is difficult to reconcile with the close juxtaposition of the bathyal Zemorrian strata across the fault.

The Oligocene to lower Miocene volcanic rocks of both the Pigeon Point and La Honda blocks were included within the Mindego Formation by Cummings and others (1962). The volcanic breccias west of the San Gregorio fault are probably of Zemorrian to early Saucesian age—thus they are partially correlative with the Mindego Basalt of the La Honda block to the east, well dated as early Zemorrian to early Saucesian (Clark, 1968, p. 177). Although extensively altered, the volcanic rocks of the Pigeon Point block apparently lack olivine and are more felsic than the olivine–bearing Mindego Basalt.

The Monterey Formation is mapped on both sides of the fault in the Pigeon Point, La Honda, and Ben Lomond blocks. The Monterey strata that crop out near Año Nuevo Point are typically more thinly bedded and more siliceous than any of the correlative strata to the east. More significantly, the siliceous strata at Año Nuevo Point yield a deeper–water fauna than the lithologi-

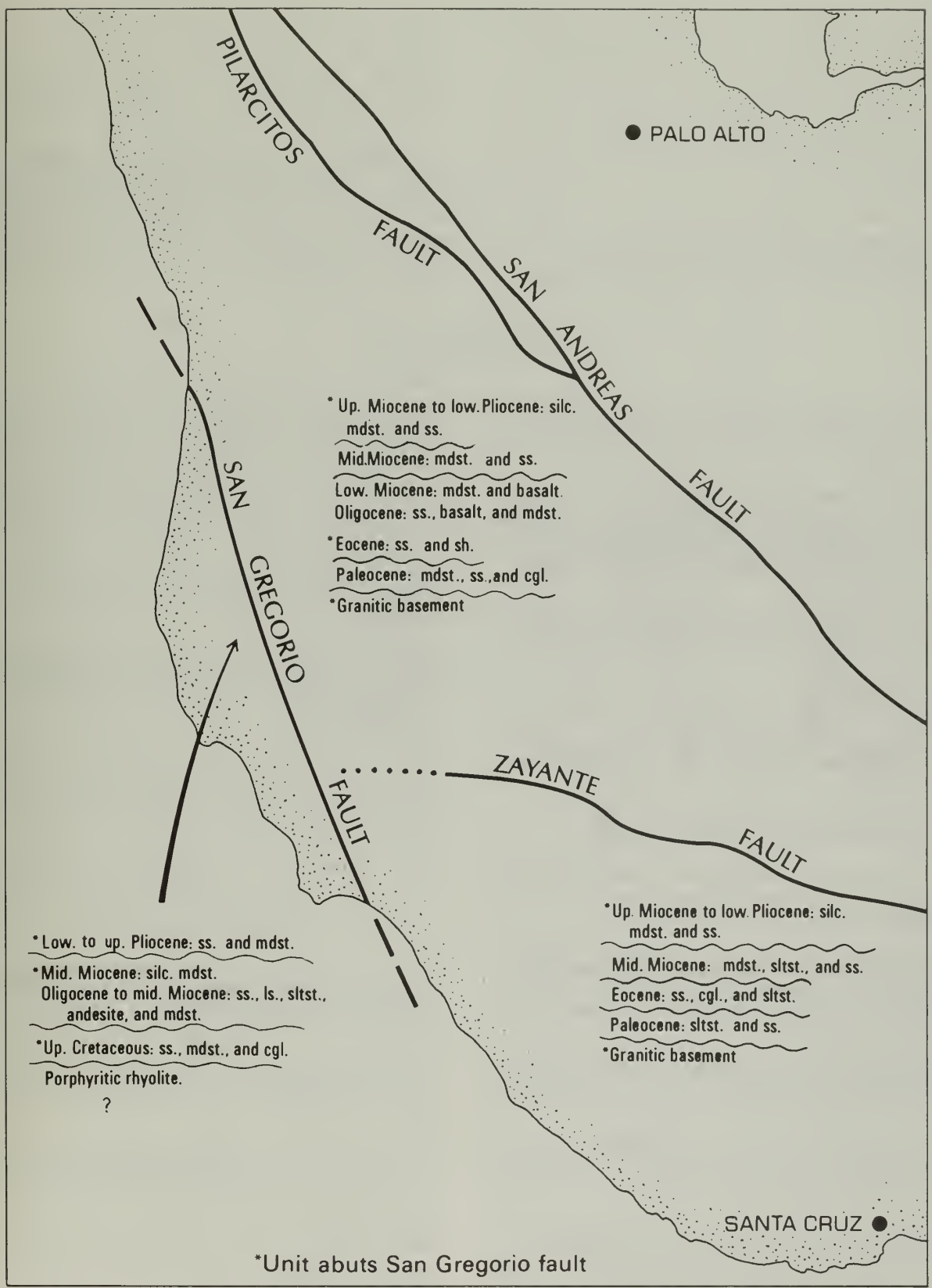

FIGURE 4. Geologic sections acrass the San Gregorio fault, Santa Cruz Mountains.

cally dissimilar sandy siltstone beds of the Monterey that occur on the southwestern slope of Ben Lomond Mountain directly across the fault. Additionally, the Vaqueros(?)–Monterey section east of Año Nuevo Point and west of the fault appears to be continuous from the lower Saucesian into the upper Relizian, whereas in the Ben Lomond block lower Relizian strata are missing, and the widely transgressive upper Relizian to lower Luisian Lompico Sandstone is generally developed at the base of the middle Miocene sequence.

One of the most striking contrasts across the San Gregorio fault is the presence of more than 2,400 m (8,000 ft) of the Santa Cruz Mudstone that abuts the fault to the east along most of its on–land trace, and its total absence to the west. The mudstone member of the Purisima that is unconformable on the Monterey Formation east of Año Nuevo Point is not only younger but also less siliceous and more nodular than the typical Santa Cruz Mudstone. Additionally, the Santa Margarita Sandstone that is typically developed at the base of the Santa Cruz Mudstone is absent to the west.

Although the Tahana Sandstone and Siltstone Member of the Purisima Formation has been mapped on both sides ot the San Gregorio fault, the regional stratigraphy of the Purisima must still be worked out before the significance of this juxtaposition can be properly evaluated. Beds that are probably correlative with the Tahana are widespread in the central and southern Santa Cruz Mountains.

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APPARENT OFFSETS OF ON–LAND GEOLOGIC FEATURES ACROSS THE SAN GREGORIO–HOSGRI FAULT TREND

By Stephan A. Graham [1] and William R. Dickinson[2]

Abstract

Campanent faults af the San Gregaria-Hasgri fault trend, raughly caincident with the present central Califarnia caastline and part af the San Andreas fault system, may have experienced abaut 115 km af Neagene right-slip. Evidence far right-slip cansists af passible pairs af affset gealagic features, including: (1) nearly identical Tertiary sequences at Paint Reyes and in the sauthern Santa Cruz Mauntains, (2) similar Cretaceaus and Oligacene-Miacene strata af the western Santa Cruz Mauntains and the narthern Santa Lucia Range, (3) the structural cantact between granitic basement and Franciscan camplex narth af Badega Head and in the narthern Santa Cruz Mauntains, (4) tectanic slabs af patassium feldspar-bearing sandstanes within the Franciscan camplex near Paint Sur and Cambria, (5) Franciscan-derived Miacene sandstane near Paint Sur and patential saurce terranes ta the sauth, and (6) Mesazaic aphialite and averlying Tertiary sectians near San Simean and Paint Sal. The suggested right-slip is definitely past-early Miacene and prabably past-middle Miacene. Because the San Gregaria-Hasgri fault trend intersects the San Andreas fault affshare sauth af Balinas, the tatal apparent affset af granitic basement alang the San Andreas fault is actually the sum af affsets an the San Gregaria-Hasgri and the San Andreas faults. Camparisan af time-displacement curves demanstrates that these twa faults accaunt far much af the past-Oligacene displacement between the Pacific and Narth American plates. Recagnitian af Neagene San Gregaria-Hasgri right-slip thus reduces considerably the apparent magnitude af right-slip alang an early Tertiary prata-San Andreas fault.

INTRODUCTION

Early geologic mapping of the central California coast demonstrated that striking stratal discontinuities exist across the San Gregorio fault (figure 1) some 50 km south of San Francisco (Branner and others, 1909). Originally mapped only as an on–land fault segment running from near the village of San Gregorio south to Año Nuevo Point, the fault now generally is considered to trend offshore near San Gregorio and to re–emerge at Pillar Point, 20 km to the northwest (figure 1), as the Seal Cove fault (e.g., Glen, 1959; Jennings and Burnett, 1961; Weber, 1974). This connection has not been verified rigorously, but a series of linear shoals extending south from the Seal Cove fault across the mouth of Half Moon Bay toward the San Gregorio fault make the connection a virtual certainty. Seismic profiling data establish that the Seal Cove segment of the San Gregorio fault trends northward offshore from San Francisco to join the San Andreas fault zone underwater south of the town of Bolinas (Cooper, 1973).

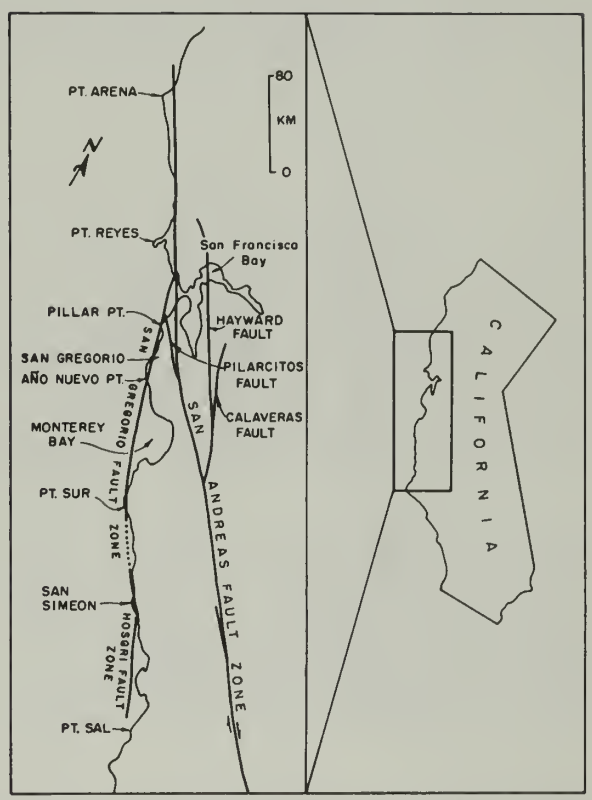

FIGURE 1. Major elements of the San Andreas fault system, central California.

South of the on–land type segment, the San Gregorio fault has been traced by seismic profiling across outer Monterey Bay and Monterey submarine canyon, and thence up Carmel submarine canyon (Greene and others, 1973). Greene and others (1973) mapped the San Gregorio fault returning ashore as the Palo Colorado fault in the northern Santa Lucia Range between Carmel and Point Sur (figure 2), and referred to the over–all trend as the Palo Colorado–San Gregorio fault zone. This paper, however, advocates an alternative to the Palo Colorado connection. Evidence is offered here to indicate that the San Gregorio fault instead is continuous, via a portion of the Sur fault zone, with the San Simeon–Hosgri fault zone (Hall, 1975) along the coast to the south (figure 1). Precise relationships between all branching and *en echelon* segments of this complex system remain unresolved, but the term San Gregorio–Hosgri fault trend will be used in this paper to designate the whole array of linked traces.

In its type area, the San Gregorio fault consists of a near vertical strand or multiple strands forming a fault zone hundreds of meters wide (Clark, 1970; Cummings and others, 1962; Web-

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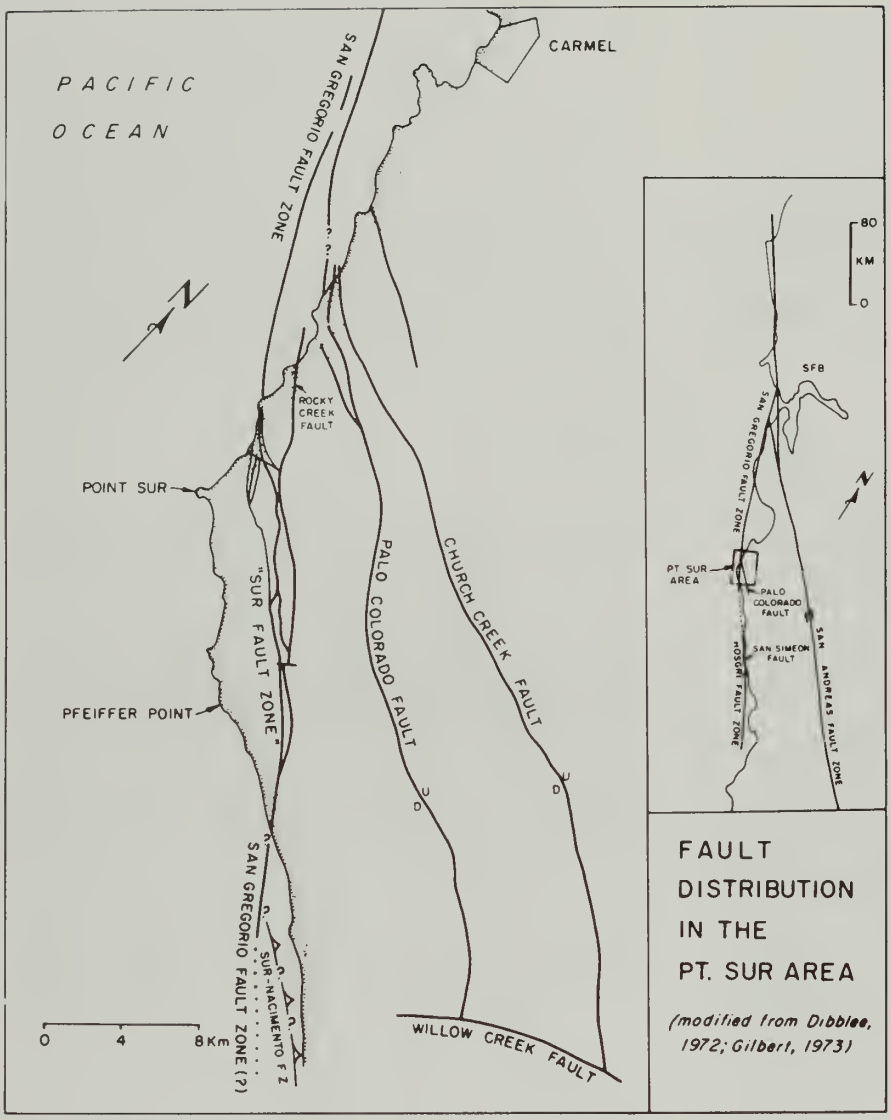

FIGURE 2. Relotionship of the Son Gregorio, Sur, ond Polo Colorodo foults in the Point Sur oreo.

er, 1974). Upper Cretaceous sedimentary rocks crop out extensively west of the fault in the San Gregorio area but are unknown east of the fault in the Santa Cruz Mountains; conversely, a well-developed Paleocene through Oligocene sequence is present in the Santa Cruz Mountains but is absent west of the fault (Cummings and others, 1962). The occurrence of generally similar Pliocene marine rocks on both sides of the fault in its type area led previous investigators to conclude that the San Gregorio fault had experienced no significant strike-slip movement (Cummings and others, 1962). However, the similarities in character and orientation of the San Gregorio fault and the San Andreas fault prompted Hill and Dibblee (1953) to suggest that the former might also be a major right-lateral strike-slip fault. The subsequent discovery of the convergence of the two faults offshore northwest of San Francisco further supports the idea that the San Gregorio and San Andreas faults are structurally related. We thus regard the San Gregorio–Hosgri fault trend as part of the San Andreas fault system. The importance of the San Gregorio–Hosgri fault trend is evidenced by its apparent control of the position of the modern central California coastline (figure 1).

THE SOUTHERN SAN GREGORIO FAULT ZONE AND RELATIONS WITH THE HOSGRI FAULT

From the head of Carmel submarine canyon, Greene and others (1973) projected the San Gregorio fault south into the Palo Colorado fault onshore (figure 2). This connection requires an abrupt bend in a fault trace that is otherwise rather straight. Data are rather poor offshore in the vicinity of the presumed connection (J. Dohrenwend, 1971; personal communication, 1974), however, and the proposed bend is therefore queried on the map of Greene and others (1973).

The Palo Colorado fault was described by Trask (1926) as one of a family of probable high-angle reverse faults that trend northwest-southeast in the northern Santa Lucia Range. Faults of this set locally thrust Salinian granitic basement rocks over lower Tertiary sedimentary rocks with dip-slip displacements of at least several hundred meters (Trask, 1926; Dickinson, 1965; Compton, 1966). Most published geologic maps of the region

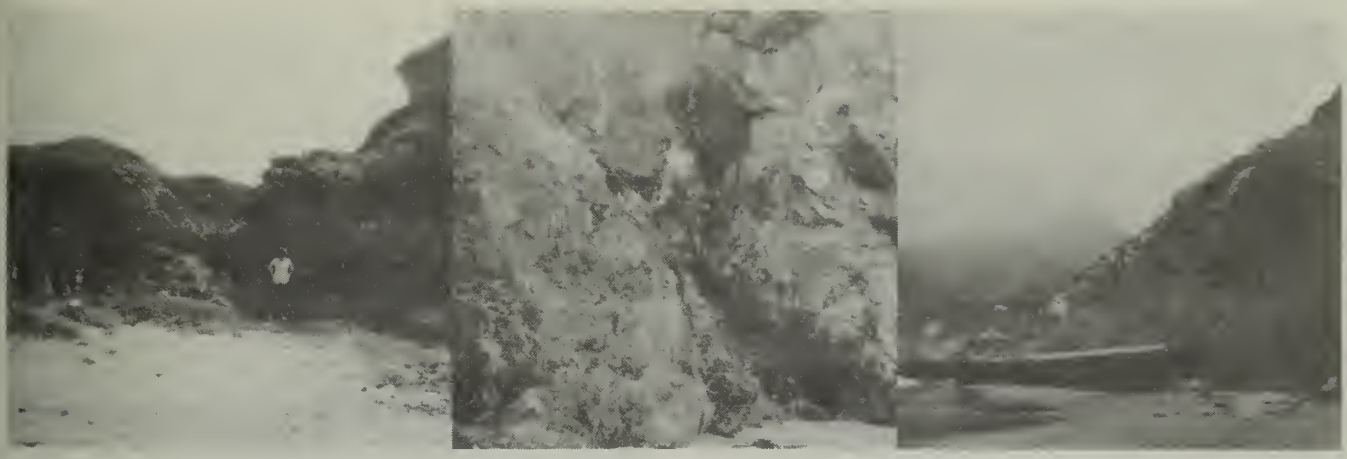

FIGURE 3. *Left,* seacliff exposure of the Pala Calarada fault (in gully) separating Paleacene (?) turbidites at right fram granitic basement at left; *center,* highly sheared granitic basement invalved in the Racky Creek fault zane; staff is 1.5 meters; *right,* retaining wall (3 meters high) at base af seacliff expasures af Rocky Creek fault zone.

have shown the Palo Colorado fault terminating to the south against the east–west Willow Creek fault (figure 2) within the granitic basement terrain of the Salinian block (Reiche, 1937; Dickinson, 1965; Dibblee, 1974). A recent basement geology map by Ross (1976) alternatively shows the Palo Colorado fault as veering more southerly to join the Coast Ridge fault zone; however, this connection was inferred solely from the distribution of charnockitic basement rocks and was not field checked by Ross.

The southern course of the Palo Colorado fault is not critical to the present discussion; more important is the presumed continuity of the San Gregorio and Palo Colorado faults. Several observations make the correlation uncertain, if not untenable. The connection between the two faults was inferred in a region where data are poor, providing an unusual resultant geometry. In its type area, the San Gregorio fault has characteristics typical of strike–slip faults, such as a broad, complex, vertical fault zone. In contrast, sea cliff exposures of the Palo Colorado fault north of Point Sur reveal a modest, meter–thick shear zone separating granitic basement and upper Cretaceous or Paleocene sedimentary rocks (figure 3), which occur in normal depositional contact nearby at Carmel. High–angle reverse faults commonly are associated with strike–slip fault zones, particularly as splays or as connecting fault segments (e.g., Dickinson, 1966), but the Palo Colorado fault has been depicted as the primary extension of the San Gregorio fault and not as an auxiliary fault (e.g., Green and others, 1973). However, the Palo Colorado fault resembles neither the San Gregorio fault in its type area nor other well–documented strike–slip faults like the San Andreas fault. Moreover, it is not more than about 50 km long, regardless of which trace is selected as its southern extension.

If the San Gregorio and Palo Colorado faults were continuous, the fault system could have no significant strike–slip component because the Palo Colorado fault, using either interpretation of its southern course, dies out within the Salinian block without disrupting the depositional patterns of sedimentary units (Graham, 1976a). Furthermore, the Church Creek high–angle reverse fault (figure 2), subparallel and nearby to the northeast, converges with the Palo Colorado fault near the coast (Dibblee, 1974) and is constrained to minimal strike–slip movement by the cross–fault occurrence of a unique graphitic–pyritic basement unit near its southern end (Wiebe, 1970; Ross, 1976). These data and evidence for an alternative southern extension of the San Gregorio fault, discussed below, seemingly disallow the Palo Colorado fault either as a major strike–slip fault or as the main southern extension of the San Gregorio fault. This conclusion does not imply, however, that the San Gregorio fault and the high–angle reverse faults of the northern Santa Lucia Range are unrelated. As will be seen, the San Gregorio fault is likely post–middle Miocene and is thus approximately synchronous with the permissive Plio–Pleistocene age of the Church Creek, Palo Colorado, and allied faults (Compton, 1966). The whole family of faults is more readily understandable in the larger context of the Salinian block and the San Andreas fault system (Graham, 1976a), which will be considered briefly in the final section of this discussion.

Where the Palo Colorado fault fails as the southern extension of the San Gregorio fault, a seemingly more viable alternative pathway extends the San Gregorio fault south from the head of Carmel submarine canyon into the onshore Sur fault zone north of Point Sur (figure 2). This pathway then diverges from the Sur zone as mapped when it trends offshore again southeast of Pfeiffer Point, and ultimately joins with the San Simeon–Hosgri fault system (Hall, 1975; Wagner, 1974) along the coast farther south (figure 2).

The Sur fault zone long has been recognized as a complex feature forming the boundary between Salinian granitic basement on the northeast and Franciscan complex on the southwest (e.g., Trask, 1926). Although this key contact is primarily a relic of underthrusting at a Mesozoic convergent continental margin (Page, 1970), the Sur zone itself also had a Neogene history of activity that likely included strike–slip movement in the Point Sur area (Gilbert, 1971; Gilbert, 1973). The actual connection of the Sur zone and the San Gregorio fault is not yet defined, but it may in part utilize an unnamed shear zone well displayed in cliffs at the mouth of Rocky Creek (figure 2). Unlike the coastal exposures of the Palo Colorado fault, the Rocky Creek fault is a shear zone several hundred meters wide, including numerous shear surfaces and gouge zones (figure 3). The steep cliffs of sheared material tend toward failure, and a massive concrete retaining wall has been constructed at the strand line at the base of the cliffs (figure 3). The Rocky Creek shear zone separates granitic intrusives on the northeast from a small structural block of Salinian schist basement on the southwest and trends into the Sur zone, 6 km to the southeast (Dibblee, 1974).

Two pieces of evidence provide additional support for the San Gregorio–Sur connection. (1) The Franciscan in the vicinity of

Point Sur (figure 4) is an unmetamorphosed, albeit structurally complex, graywacke–mudstone assemblage in which detrital K–feldspar is present (Gilbert, 1971). In contrast, the Franciscan complex in the on–land exposures in the Lopez Point area nearby to the south (figure 4) is a blueschist–facies metamorphic sequence in which K–feldspars are absent (Gilbert, 1971). Strike–slip movement on the San Gregorio fault utilizing the Sur zone in the Point Sur area readily explains the striking local contrasts in Franciscan facies observed in the area. Furthermore, as discussed below, the unmetamorphosed Franciscan of the Point Sur area apparently is offset in a right–lateral sense from similar rocks far to the south, thus supporting the Sur pathway. (2) A small fault–bounded slice of Miocene sandstone within the Sur fault zone (figures 4 and 5) is composed exclusively of Franciscan–derived detritus (Trask, 1926; Brooke, 1957; Gilbert, 1971; Graham, 1976a). This sandstone crops out less then 2 km from Salinian granitic basement known to be subaerially exposed through much of Miocene time (Graham, 1976a), yet contains no Salinian detritus. Although special circumstances could be invoked to explain the presence of the Franciscan–derived sandstone, right–lateral strike–slip on a San Gregorio–Sur fault system offers the most convenient explanation.

Evidence for the course of the San Gregorio fault south of its presumed divergence from the Sur zone offshore southeast of Pfieffer Point is circumstantial. We infer a near–shore fault from Pfieffer Point to the San Simeon area primarily on the basis of the apparent on–strike alignment of the San Gregorio and Hosgri faults (figure 2). Some previous investigators (Hoskins and Griffiths, 1971; Wagner, 1974) have shown the Hosgri fault trending out to sea south of San Simeon (figure 1) rather than emerging onshore as the San Simeon fault (Hall, 1975). Hall's Point Sur–San Simeon ophiolite–Tertiary rock offset (discussed below) depends on the validity of the latter interpretation. The presumed connection lies, as is the case with the San Gregorio–Palo Colorado–Sur problem, near shore in shallow water where acoustic data of good quality are difficult to obtain. The near–perfect alignment of the prominent San Gregorio and Hosgri fault segments through the San Simeon fault segment seems to us unlikely to be a chance phenomenon, even though the details of the San Gregorio–Hosgri connection are uncertain. Furthermore, if our offset criteria are correct, such a connection is required.

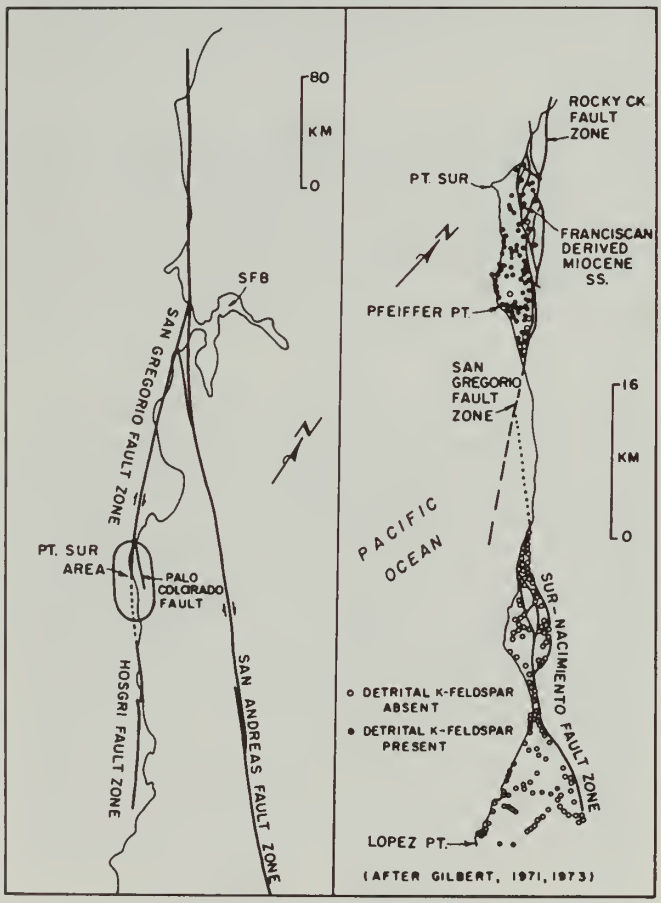

FIGURE 4. Course af the San Gregorio foult in the Point Sur oreo, ond cross–foult contrasts in Fronciscon sondstone composition ond metomorphic grade.

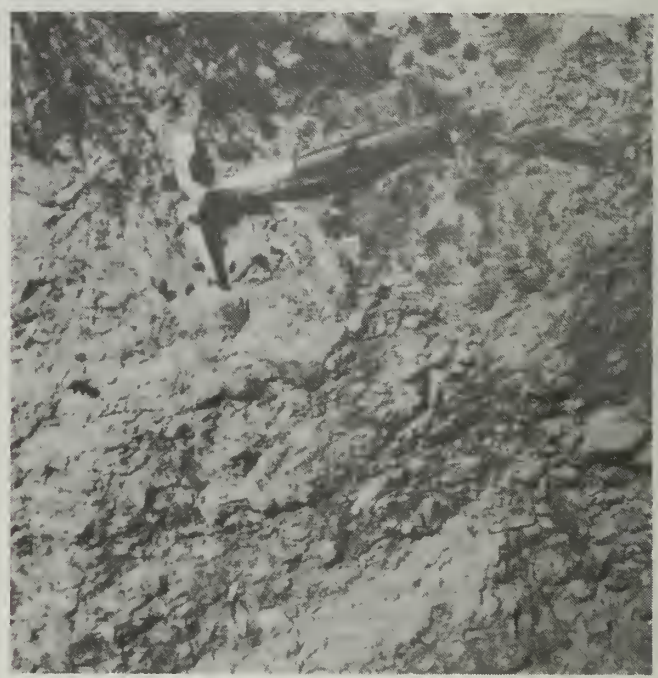

FIGURE 5. Miocene canglomerote exposed in foult slice neor Point Sur (see figure 4). Clasts are exclusively Fronciscan sedimentory ond igneous lithologies.

EVIDENCE FOR RIGHT–LATERAL STRIKESLIP

A family of geologic features apparently exhibits offset in a right–lateral sense along the San Gregorio–Hosgri trend as defined above (figures 6 and 7). These offset pairs include rock bodies, sedimentary units and inferred source terranes, a pre–San Gregorio fault, and a late–Cretaceous basin margin. The latter two are linear features whose intersection with the San Gregorio–Hosgri fault trend produces piercing points from which, ideally, the best estimates of offset are obtained (Crowell, 1962). Nevertheless, because of uncertainties inherent in the estimation of the boundaries or positions of all of these features, offset values are given in terms of ranges. Assuming valid cross–fault correlations, the overlap of offset ranges indicates approximately 115 km of right–lateral strike–slip on component faults of the San Gregorio–Hosgri fault trend (figure 7). Few, if any, of the offset pairs discussed below individually constitute unique evidence. Taken together, however, we feel that they present a compelling argument for major right–lateral strike–slip on faults of the San Gregorio–Hosgri fault trend.

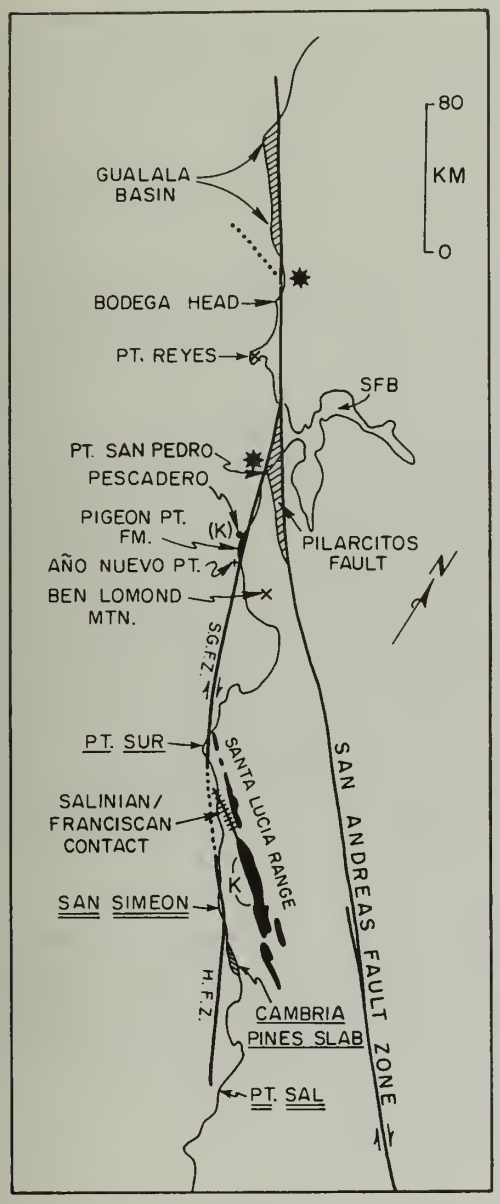

FIGURE 6. Mop of geologic feotures offset in a right–loterol sense olong the Son Gregorio–Hosgri foult trend. See text for discussion.

Bodega/Gualala Fault – Pilarcitos Fault Offset Pair

The Pilarcitos fault (figures 1 and 6) lies along the spine of the San Francisco Peninsula subparallel to the San Andreas fault, truncated to the south by the San Andreas fault and to the north offshore by the San Gregorio fault (modification of Cooper, 1973, based on later data; K. LaJoie, personal communication, 1976; Graham, 1976a). The Pilarcitos fault, although lying west of the modern San Andreas fault (figure 6) is the local structural boundary between Franciscan complex on the northeast and Salinian granitic basement on the southwest, and, thus, is considered to be an inactive and cut–off trace of the San Andreas fault (e.g., Nilsen and Simoni, 1973). Poorly exposed and poorly studied lower Tertiary rocks unconformably (?) overlie Franciscan complex within the structural block between the Pilarcitos and the San Andreas faults (Brabb, 1970).

Far to the north, the last on–land exposures of granitic basement of the Salinian block occur at Bodega Head immediately west of the San Andreas fault as it heads offshore (figure 6). Where the fault re–emerges 22 km to the north, the terrain west of the fault is underlain by a thick sequence of Cretaceous through Eocene sedimentary rocks comprising the Gualala basin (Wentworth, 1968). The basement of the Gualala basin is not known with certainty, but spilitic basalts, possibly of Franciscan affinity, structurally and perhaps stratigraphically underlie the oldest sediments (Wentworth, 1968). If the Gualala basin is underlain by Franciscan complex, then a structural contact between Franciscan complex and Salinian granitic basement analogous to the Pilarcitos fault must exit between the Gualala basin and Bodega Head and be truncated offshore between those points by the San Andreas fault (figure 6). We conclude that these two Franciscan–granitic basement contacts may be equivalent and offset from each other in a right–lateral sense along a San Gregorio–San Andreas pathway (stars in figure 6).

If perfectly known, offset fault traces would provide piercing points in the San Gregorio–San Andreas fault plane which would yield accurate estimates of the magnitude of offset. Unfortunately, both intersections lie offshore in regions of poor or non–existent data. Consequently, we present an offset range (figure 7) with a minimum based on the position of the Bodega Head exposures (92.5 km) and a maximum based on the southern limit of exposures of the Gualala basin (115 km).

The Gualala–Pilarcitos correlation can be tested. If the two faults are offset equivalents, the Gualala basin sedimentary units are offset lateral equivalents of the lower Tertiary sedimentary rocks at Pt. San Pedro in the Santa Cruz Mountains (figure 6). Both sequences are deep–sea fan facies with northwesterly paleocurrent directions (Wentworth, 1968; Chipping, 1972). A modest amount of petrographic data are presently available for these areas, but more must be obtained to test the correlation adequately.

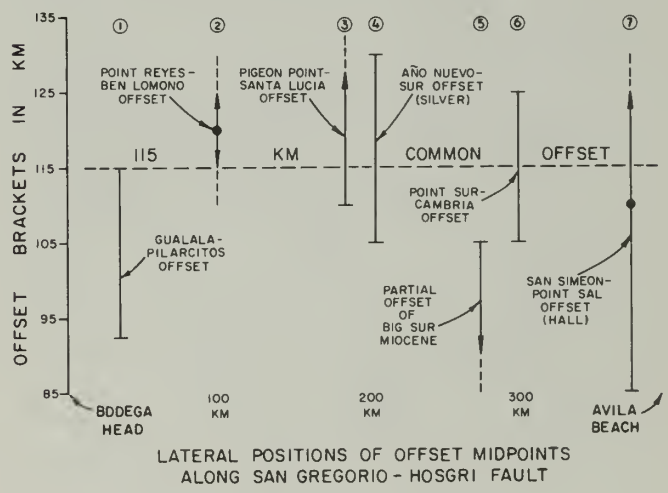

FIGURE 7. Offset ronge chort for suggested offset pairs.

Point Reyes Section – Ben Lomond Mountain Section Offset Pair

The granitic basement of the Point Reyes Peninsula (figure 6) is blanketed partially by erosional remnants of Paleocene and more extensive Neogene sedimentary rocks (figure 8). The Neogene units comprise two unconformity–bound sedimentary packages (Galloway, 1976; Blake and others, 1974): a Miocene

couplet of shallow marine sandstone overlain by basinal siliceous shales(Laird Sandstone and Monterey Formation)and an upper Miocene–Pliocene couplet of shallow marine sandstone and overlying basinal mudstones ("sandstone and mudstone near Drakes Bay"). The Paleocene rocks are primarily conglomerate, with lesser amounts of sandstone and mudstone. Our observations suggest that the Paleocene rocks, preserved only at Point Reyes proper, were deposited in an inner fan or channelized mid–fan environment (terminology of Ricci–Lucchi, 1975) on a Paleocene deep–sea fan. This interpretation is substantiated by a probable lower bathyal (> 2000–meter water depth) foraminiferal fauna obtained from the mudstone (A. J. Galloway, written communication, 1975).

The Santa Cruz Mountains to the south of San Francisco are underlain by a relatively complete Tertiary section of rocks, but the southern flank of the Ben Lomond Mountain (figure 6) basement uplift displays an abbreviated Tertiary section (figure 8). The Ben Lomond Mountain section includes a Paleocene unit (Locatelli Formation) unconformably overlain by unconformity–bound, shallow marine sandstone/basinal mudstone packages (Clark, 1966) of middle Miocene (Lompico Sandstone/Monterey Formation) and late Miocene–Pliocene age (Santa Margarita Sandstone/Santa Cruz Mudstone). The Paleocene Locatelli Formation contains a shallow marine fauna near its base, but a deep marine fauna in its upper part (Clark, 1966; Clark, 1968). We suggest that the Point Reyes–Ben Lomond Mountain sections, with their unusual Paleocene/middle Miocene/upper Miocene–Pliocene sedimentary packaging, are lateral equivalents offset by the San Gregorio fault (x's in figure 6; figure 7). Clark (1968), in his thorough study of the southern Santa Cruz Mountains, noted the virtual identity of the Point Reyes and Ben Lomond Mountain Neogene sections. The spottily preserved Paleocene rocks of both areas are deep–water marine facies, although perhaps deposited in differing submarine fan environments. In addition, a reconnaissance study of Salinian basement rocks by Ross (1972) revealed an abundance of alaskite dikes in only two areas, the Point Reyes and Ben Lomond Mountain areas.

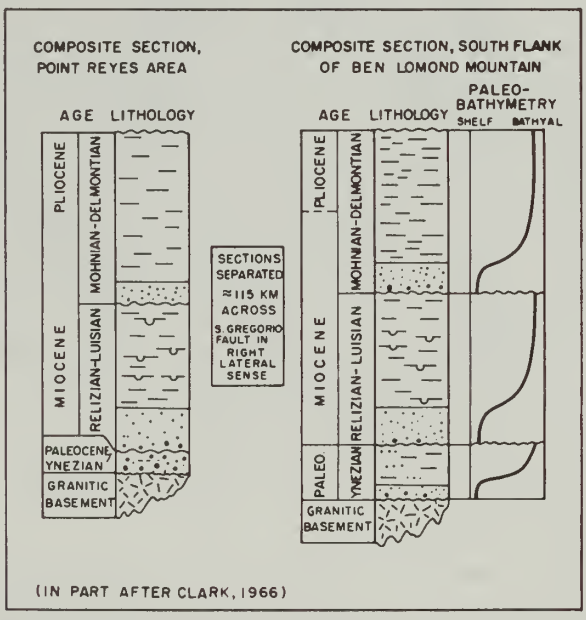

FIGURE 8. Generolized strotigrophic sections in the Point Reyes orea ond on the south flonk of Ben Lomond Mountoin.

The offset rock bodies offer no absolute constraints on the amount of right–slip. A minimum of 115 km is based on the southern limit of Eocene rocks cropping out on the northern flank of Ben Lomond Mountain, while the most reasonable apparent value is about 120 km.

Pigeon Point Formation – Santa Lucia Cretaceous Offset Pair

The upper Cretaceous Pigeon Point Formation (Hall and others, 1959) crops out extensively west of the San Gregorio fault from San Gregorio to Año Nuevo Point (figure 6), but is unknown directly across the fault to the east in the Santa Cruz Mountains (Cummings and others, 1962). The conglomerate–mudstone–sandstone succession is best characterized as a regressional/progradational deep–sea fan–to–shelf sequence (Lowe, 1972). Approximately fifty paleocurrent measurements (Wentworth, 1960; Paredes, 1960) obtained from a variety of turbidite –associated paleocurrent indicators suggest dispersal to the south–southwest. Pigeon Point Formation conglomerates, common in the channelized fan facies, contain some Salinian basement–derived clasts, but are composed principally of well–rounded clasts of acidic to intermediate composition, varicolored, porphyritic volcanics (Tyler, 1972). The ultimate source of these volcanic clasts, common in Coast Range Cretaceous and Tertiary sedimentary rocks, remains unknown.

Cretaceous sedimentary rocks are present from San Gregorio to Año Nuevo Point, but occur nowhere else on the Salinian block from San Francisco to Monterey. Rocks very similar to the Cretaceous Pigeon Point Formation in facies and composition rest on basement south of Monterey in the vicinity of Carmel (the Carmelo Formation, Bowen, 1965). However, those rocks are Paleocene, while the Pigeon Point Formation is entirely upper Cretaceous, based on molluscs we have found in the uppermost shallow marine facies of Lowe (1972). Cretaceous sedimentary rocks do crop out a few tens of kilometers farther south of Carmel (figure 6) in the Point Sur (Trask, 1926) and Lucia (Reiche, 1937) quadrangles, and then in a nearly continuous strip down the Santa Lucia Range to the Transverse Ranges (Jennings, 1958; Jennings and Strand, 1958).

The Cretaceous strata of the northern Santa Lucia Range are virtually unstudied, but abundant shallow marine fossils occurring locally near the base of the sequence (Reiche, 1937) may indicate that the rocks are, in part, shallow marine in origin. Twenty kilometers inland along depositional strike to the southeast in the upper Arroyo Seco area, upper Cretaceous sandstones and conglomerates, bearing evidence of southwesterly directed paleocurrents, likely were deposited as a submarine canyon-fill (Ruetz, 1976). Apparently two different clast assemblages characterize the upper Cretaceous conglomerates, a porphyritic volcanic-dominated suite in northern outcrops and a Salinian basement-dominated suite in southern outcrops (Reiche, 1937; Ruetz, 1976).

The Pigeon Point Formation thus may be offset from the porphyritic volcanic–bearing Cretaceous rocks of the northern Santa Lucia Range by right–slip on the San Gregorio fault (black areas in figure 6; figure 7). Limited paleocurrent and paleoenvironmental data are compatible with such a correlation. In the Arroyo Seco area, the overlap of Cretaceous rocks by Paleocene deep–sea fan deposits defines the local northern limit of the Cretaceous basin (Ruetz, 1976). The limit of the Cretaceous basin along depositional strike at the coast can be no farther south than the Carmel area, where Paleocene rocks rest

on basement. The basin edge could lie as far south as the Palo Colorado fault (figure 2) if the sandstones exposed where the fault intersects the coast are Tertiary (W. R. Dickinson, unpublished data) rather than Cretaceous (Trask, 1926; Dibblee, 1974). The Cretaceous basin edge constitutes a linear feature which would yield a good estimate of San Gregorio offset if the basin edge was better defined near the coast. No Paleocene strata are associated with the Pigeon Point Formation to define the Cretaceous basin margin west of the San Gregorio fault, but we take the shallow marine facies capping the Pigeon Point Formation to signal immediate proximity to a Cretaceous basin margin. Assuming that the Palo Colorado coastal sandstones are Paleocene as inferred here, the Cretaceous basin margin is offset by a minimum of 110 km (figure 7).

Preliminary comparison of Oligocene–Miocene rocks overlying the Pigeon Point Formation with coeval strata of the northern Santa Lucia Range supports the cross–fault Cretaceous ties. Upper Oligocene–lower Miocene shallow–marine sandstone and interbedded basaltic volcanics at Pescadero and coeval deep–marine mudstone at Año Nuevo Point (figure 6; Clark and Brabb, 1977, and this volume) suggest a south–facing paleoslope. Similarly, a southwest–facing late Oligocene–early Miocene paleoslope (not shown in figure 6) is documented for the northern Santa Lucia Range (Graham, 1976a,b). In addition, restoration of 115 km of right–slip places the Pescadero basalts on projection from a trend of upper Oligocene–lower Miocene bimodal volcanics (e.g., Ernst and Hall, 1974; Graham, 1976a) cropping out south of and parallel to the Cretaceous outcrop band in the Santa Lucia Range at the southwest margin of the Salinian block (figure 6).

Offset of Offshore Gravity Ridge

Silver (1974) proposed that an offshore linear gravity "high" was offset 90 km by right–lateral strike–slip on the San Gregorio fault. The southern flank of the feature comes ashore near Año Nuevo Point west of the fault and was suggested to be offset from the edge of Salinian basement marked by the Sur fault where it trends offshore north of Point Sur. Remeasuring the indicated offset to the edge of Salinian basement south of Point Sur, we suggest a range of 105 to 130 km (figure 7) for Silver's offset.

Point Sur Franciscan – Cambria Pines Slab Offset Pair

A cross–fault contrast in metamorphic facies in the Franciscan complex serves to define the probable course of the San Gregorio fault near Point Sur (figure 4). From the Point Lopez area south, the Franciscan complex contains extensive mélange units, is metamorphosed to varying degrees, and generally is devoid of detrital K–feldspar (Gilbert, 1971; Hsu, 1969). However, an unmetamorphosed K–feldspar–bearing Franciscan graywacke sequence is exposed near Cambria (Hall, 1974), and we suggest that this Cambria Pines slab (Hsu, 1969) is the offset equivalent along the San Gregorio–Hosgri trend of the unmetamorphosed K–feldspar–bearing Franciscan complex at Point Sur (figures 4 and single underlines in figure 6). Matching the north end of the Cambria Pines slab with the north end of the Point Sur block yields a minimum offset of 105 km. The southern end of the Cambria Pines slab must lie under Estero Bay, based on the on–land distribution of Franciscan lithologies (Hsu, 1969; Hall, 1973), thus setting the probable upper limit of offset at 125 km.

Point Sur Miocene Sandstone–Franciscan Source Terrane Offset Pair

As discussed earlier, the position of a Franciscan–derived Miocene sandstone caught within the San Gregorio–Sur fault zone east of Point Sur (figures 4 and 5) is incompatible with its immediate proximity to Salinian basement. At least 60 km of right–slip on the San Gregorio–Hosgri fault trend is required to provide an adequate source terrane for the Miocene sandstone. The offset of the sandstone cannot exceed 105 km, however, because it contains no volcanic clasts derived from the Cambria Felsite as do Miocene sandstones in the Cambria area (Hall, 1974). This maximum is less than the minimum offset indicated for certain of the offset pairs (figure 7), but the lack of overlap poses no problem because the Miocene sandstone is in a fault–bounded slice which likely was incorporated in the fault zone at an intermediate distance.

San Simeon Ophiolite–Point Sal Ophiolite Offset Pair

Hall (1975) reported the probable offset of a Mesozoic ophiolite and overlying distinctive Tertiary sequence from Point Sal to the San Simeon area along the San Simeon–Hosgri segment of the then unrecognized larger San Gregorio–Hosgri fault trend (double underlines in figure 6). Hall claimed a minimum of 80 km of offset, but in reexamining local relations we suggest a minimum of 85 km from the north end of San Simeon outcrops to the limit of outcrops at Point San Luis. An offset value of 110 km is gained from the center of the outcrop pattern west of the fault to the center of the outcrops east of the fault (figure 7).

TIMING OF MOVEMENT

Geologic relations indicate that the offset of the Point Sal–San Simeon ophiolite–Tertiary sequence by the Hosgri fault segment was accomplished 5–13 million years ago (Hall, 1975). Most of the indicators on the San Gregorio segment merely indicate a post–Cretaceous age, but two offset pairs are more specific. The fault slice of Miocene sandstone near Point Sur contains *Crassostrea titan subtitan* (Trask, 1926; Graham, 1976a). Although ranging throughout the Miocene, this mollusc is most typical of lower Miocene strata in the Cambria area (Hall, 1974). We thus infer that major right–slip involving the sandstone is probably post–lower Miocene. The Point Reyes–Ben Lomond Mountain offset pair relies on similar middle Miocene and upper Miocene–Pliocene sections. If valid, this correlation implies that right–slip may have commenced by at least late Miocene time, and the sub–upper Miocene unconformity could reflect this event. A late Miocene or conservative post–middle Miocene age for the initiation of strike–slip is compatible with the timing suggested for the Hosgri segment.

At 6 cm/yr, the rate of movement on the modern San Andreas fault (e.g., Dickinson and others, 1972), the entire 115 km of indicated right–slip could be accomplished in less than 2 million years. At least modest Holocene movement on elements of the San Gregorio–Hosgri fault trend is indicated by the local thrusting of Miocene rocks over terrace deposits at Año Nuevo Point (Clark, 1970; Weber and LaJoie, 1977), by probable offsets of the sea floor locally (Greene and others, 1973; Wagner, 1974), and by seismicity (Gawthrup, 1977). However, the major period of movement may well have been earlier.

THE ROLE OF THE SAN GREGORIO–HOSGRI FAULT TREND IN THE SAN ANDREAS FAULT SYSTEM

The assumption of approximately 115 km of post–middle Miocene right–lateral strike–slip on faults of a San Gregorio–Hosgri fault trend connecting with the San Andreas fault implies that the total offset of Salinian basement by the San Andreas fault is only an apparent number integrating the offsets of both the San Gregorio and the San Andreas faults. The minimum total offset (510 km) is based on the northernmost on–land exposures of Salinian basement at Bodega Head (figure 9), while a maximum estimate (600 km) assumes granitic basement offshore to near Point Arena (Silver and others, 1971). Deducting 115 km of San Gregorio–Hosgri right–slip from the 600/510 km maximum/minimum on the San Andreas total leaves 485/395 km maximum/minimum of right–slip on the San Andreas fault zone *sensu strictu* (figure 9). Post–Oligocene ("modern") San Andreas right–slip, all based on cross–fault ties south of the San Gregorio–San Andreas juncture and thus unaffected by it, amounts to approximately 310 km (Dickinson and others, 1972; Matthews, 1976). Consequently, since no major right–slip faults other than the San Gregorio–Hosgri trend are known to intersect the San Andreas fault zone, the difference between the true San Andreas basement offset (having removed the San Gregorio–Hosgri component) and the post–Oligocene San Andreas right–slip must be a measure of right–slip on a pre–Oligocene proto–San Andreas fault roughly coincident in central California with the trace of the "modern" San Andreas fault zone (figure 9). Proto–San Andreas right–slip thus amounts to 175/85 km maximum/minimum.

The timing of movement on such a proto-San Andreas fault has been discussed elsewhere (e.g., Dickinson and others, 1972; Nilsen and Link, 1975), but it must certainly be pre-Eocene to honor the Butano-Point of Rocks cross-fault tie (Clark and Nilsen, 1973). An intra-Paleocene age is suggested by unconformable relations in nearby areas (Graham, 1976a, b). Significantly, however, consideration of right-slip on the San Gregorio-Hosgri fault trend reduced by at least a third and perhaps by two-thirds the apparent right-slip on the proto-San Andreas fault were the San Gregorio-Hosgri trend not considered. Furthermore, if Sierran basement east of the San Andreas fault underlies Tertiary basin fill (queried, dotted line in figure 9) northwest of its outcrop limit, and if Bodega Head west of the fault is close to the northern limit of Salinian basement, restoration of Neogene San Gregorio-Hosgri and San Andreas right-slip accounts for all basement separation. In those extreme conditions, a proto-San Andreas fault coincident with the modern San Andreas fault in central California is without support.

The right–slip history of the San Andreas fault is conveniently displayed in a time–versus–displacement graph (figure 10). Curve A, Figure 10, is the San Andreas fault time–displacement curve of Dickinson and others (1972) and Nilsen and Link (1975), modified in accordance with a Miocene–Pliocene boundary near 5 M.Y.B.P. (see Graham, 1976a, for further discussion). The curve clearly shows the two–stage nature of the history of the San Andreas fault. The dotted modification of the San Andreas curve prior to 60 M.Y.B.P. represents the effect of disregarding San Gregorio–Hosgri right–slip, while the solid curve considers San Gregorio–Hosgri right–slip and hence is the "true" San Andreas time–displacement curve.

Curve B, Figure 10, represents the history of relative movement between the Pacific and North American plates (Atwater

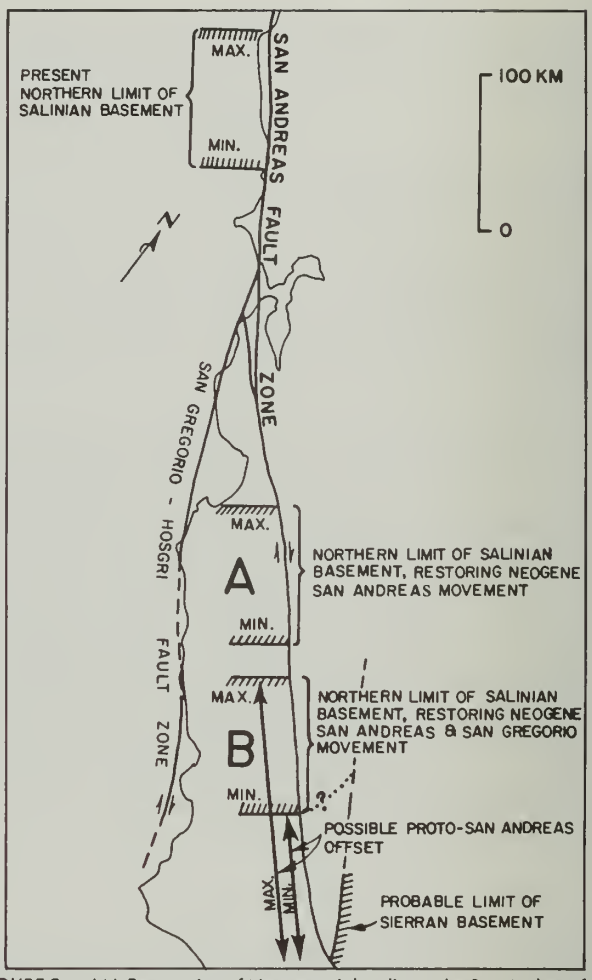

FIGURE 9. (A) Restaration af Neagene right–slip an the San Andreas fault alane, and (B) on the San Andreas fault plus San Gregario–Hasgri fault trend. Remaining affset af granitic basement not accaunted far by Neogene San Andreas and San Gregario–Hasgri right–slip may be a measure af right–slip an a prato–San Andreas fault.

and Molnar, 1973). Within the limits of uncertainty inherent in both curves, it is apparent that most movement between the two plates has been accomplished solely by the San Andreas fault for at least the past six million years. Between that time and the early Miocene, the two curves diverge, but most of the plate motion can be distributed between the San Andreas and San Gregorio–Hosgri faults. The latter is probably best regarded as an offshore strand of the former, and as such, probably absorbed a large proportion of the relative motion between the Pacific and North American plates prior to Pliocene time.

These data thus constitute a compromise between two extreme views of the evolution of the San Andreas fault: a two–stage proto–San Andreas history (e.g., Suppe, 1970), and a single–stage history involving Neogene slicing and extension of Salinian basement via the San Andreas fault and a system of allied faults (Johnson and Normark, 1974). Our consideration of the San Gregorio–Hosgri fault trend indicates that there was an episode of proto–San Andreas right–slip, albeit considerably more modest than previously supposed. In addition, however, the San Andreas fault clearly is the major component in a larger Neogene to recent San Andreas fault system of which the San Gregorio–Hosgri fault trend is a part. The proto–San Andreas right–slip episode may have entailed an extensive fault system analogous to the Neogene San Andreas system, as suggested by

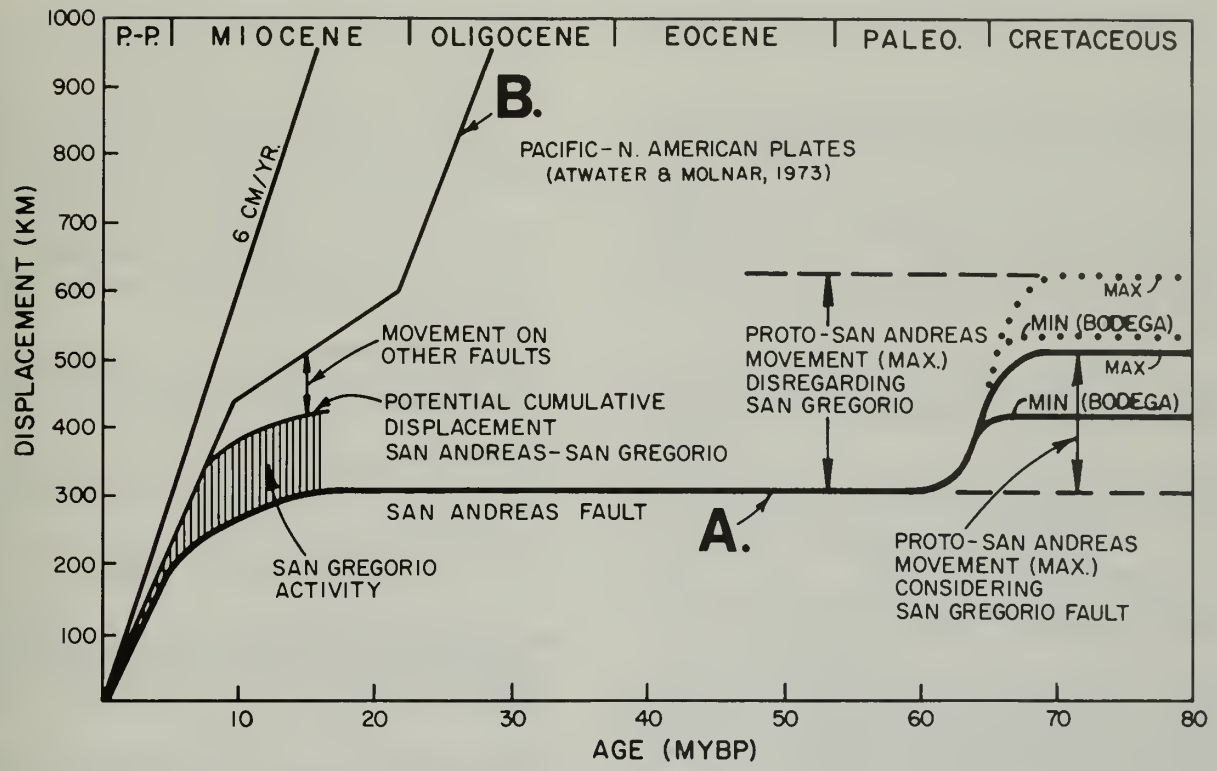

FIGURE 10. Time–offset curves. (A) Son Andreos foult curve (Dickinson ond others, 1972; Nilsen ond Link, 1975) modified in occord with o Miocene–Pliocene boundory ot obout 5MYBP ond to display the effect of Son Gregorio–Hosgri foult zone right-slip; (B) Relotive motion of the Pocific ond North Americon plotes. See text for discussion.

the early Tertiary continental borderland configuration (Nilsen and Clarke, 1975), but the details of such a system remain uncertain. The proto–San Andreas fault system possibly was the structural resolution of early Tertiary oblique subduction, rather than a transform fault system like the modern San Andreas fault system. This inference is compatible with reconstructions showing late Cretaceous–early Tertiary oblique convergence between the Farallon and North American plates (Coney, in press).

Acknowledgments

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ORIGIN AND DEVELOPMENT OF THE LOMPOC–SANTA MARIA PULL–APART BASIN AND ITS RELATION TO THE SAN SIMEON–HOSGRI STRIKE–SLIP FAULT, WESTERN CALIFORNIA

By Clarence A. Hall, Jr.*

Abstract

A model is proposed to account for the distribution of Cretaceous and Eocene sedimentary rocks, and distinctive Tertiary igneous, sedimentary, and volconiclostic rocks that lie within the western Transverse Ranges and the Santa Mario-Lompoc region, Santa Barbara County, California. Comparisons of lithologies and stratigraphic sections tend to support the hypothesis that the Tertiary Santo Morio-Lompoc basin is a pull-apart structure that began to form about 14 million years ago. Following deposition of the late Tertiary sediments, the western part of the basin was displaced, since the Pliocene, nearly 80 to 95 km to the northwest along the San Simeon-Hosgri fault zone.

INTRODUCTION

A speculative model is proposed to account for the distribution of Tertiary igneous, sedimentary, and volcaniclastic rocks that lie within the Santa Maria–Lompoc region, Santa Barbara County, California.

Geologic mapping, analyses of core holes and well data (Hall, 1977), and preliminary field investigations southeast of Santa Maria, California, suggest the presence of the Santa Maria River fault (figure 1) and that the Santa Maria River-Foxen Canyon-Little Pine fault zone (figure 1) may extend more than 100 km to the southeast. Work on this fault zone has brought to light some provocative geologic relationships which provide support for several structural models for the development of Tertiary marine basins along the coast of California and relatively recent movement on a major fault system in the region. In addition, this work suggests the presence of the inferred Lompoc-Solvang fault, which in large measure appears to represent the northwestern structural margin of the Transverse Ranges.

STRATIGRAPHY

Within 3 to 4 km immediately northeast of the Santa Maria River fault (Hall, 1977; and figure 1) the following Mesozoic and Tertiary rock units are present: (1) Franciscan mélange (thickness unknown), (2) unnamed Cretaceous rocks (more than 457 m), (3) Sespe–Lospe formations (152 m), (4) Vaqueros–Rincon formations (304 m), (5) Obispo Formation (335–609 m), (6) Point Sal or Lower Monterey Formation (304 m), and (7) Monterey Formation (1,066 m) (table 1). The Sespe–Lospe formations are not known to be present within 3 to 4 km southwest of the Santa Maria River fault. Within 9.7 km southwest of the Santa Maria River fault the following rock units are present: (1) Franciscan mélange (thickness unknown), (2) Sespe-Lospe formations (609 m), (3) Point Sal Formation (228 m), (4) Monterey Formation (629 m), (5) Sisquoc Formation (498 m), (6) Foxen Mudstone (88 m), and (7) Careaga Sandstone (43 m) (Woodring and Bramlette, 1950; and figure 2).

Although the stratigraphy northeast and southwest of the Santa Maria River fault is markedly different (i.e., Cretaceous rocks, Vaqueros Sandstone, and Rincon Shale) and, in part, Sespe–Lospe are absent in the Santa Maria Valley area, the most significant difference is the absence of between 335 m and 610 m of volcanic rocks, including volcanic ash (Obispo Formation) within a distance of 35 to 40 km southwest of the fault, and the presence of the Tranquillon volcaniclastic rocks, of the same age as the Obispo Formation, on the southwest margin of the basin more than 35 km to the south (figure 1).

TERTIARY BASIN HISTORY

At least three models can be proposed to account for the absence of rock units with distinctive lithologies, namely the Vaqueros, Rincon, and Obispo formations, southwest of the Santa Maria River fault: (1) strike–slip movement of tens of kilometers along the fault bringing into juxtaposition markedly different stratigraphic sections; (2) the area between the Santa Ynez Mountains and the Santa Maria River was a topographic high during the time when the Vaqueros and Rincon formations were being deposited elsewhere in the region, and the Obispo–Tranquillon volcanic rocks have been eroded from this region; and (3) the development of a pull–apart basin following the deposition of the Vaqueros, Rincon, and Obispo–Tranquillon formations (the formation of pull–apart basins is discussed by Crowell, 1974).

Large post–Monterey Formation or Obispo–Tranquillon volcanic rock strike–slip movement (first hypothesis) along the Santa Maria River fault is difficult to test. If right–slip along the fault did occur, the Obispo volcanic rocks formerly near the intersection of the Santa Maria River and Santa Maria Mesa faults (figure 1) would have been moved northwestward and now would be buried beneath the Pismo sand dunes or would lie below San Luis Bay in the Pacific Ocean (Jennings, 1959; Hall and Corbató, 1967; Hall, 1973).

The second hypothesis, that prior to the deposition of the Monterey shales the area between the Santa Ynez Mountains and the Santa Maria River fault was a topographic high, or that the Vaqueros, Rincon, and Obispo Formations were deposited and subsequently eroded away, can explain the distribution of the Tertiary rocks. Cretaceous rocks are absent in this area, but

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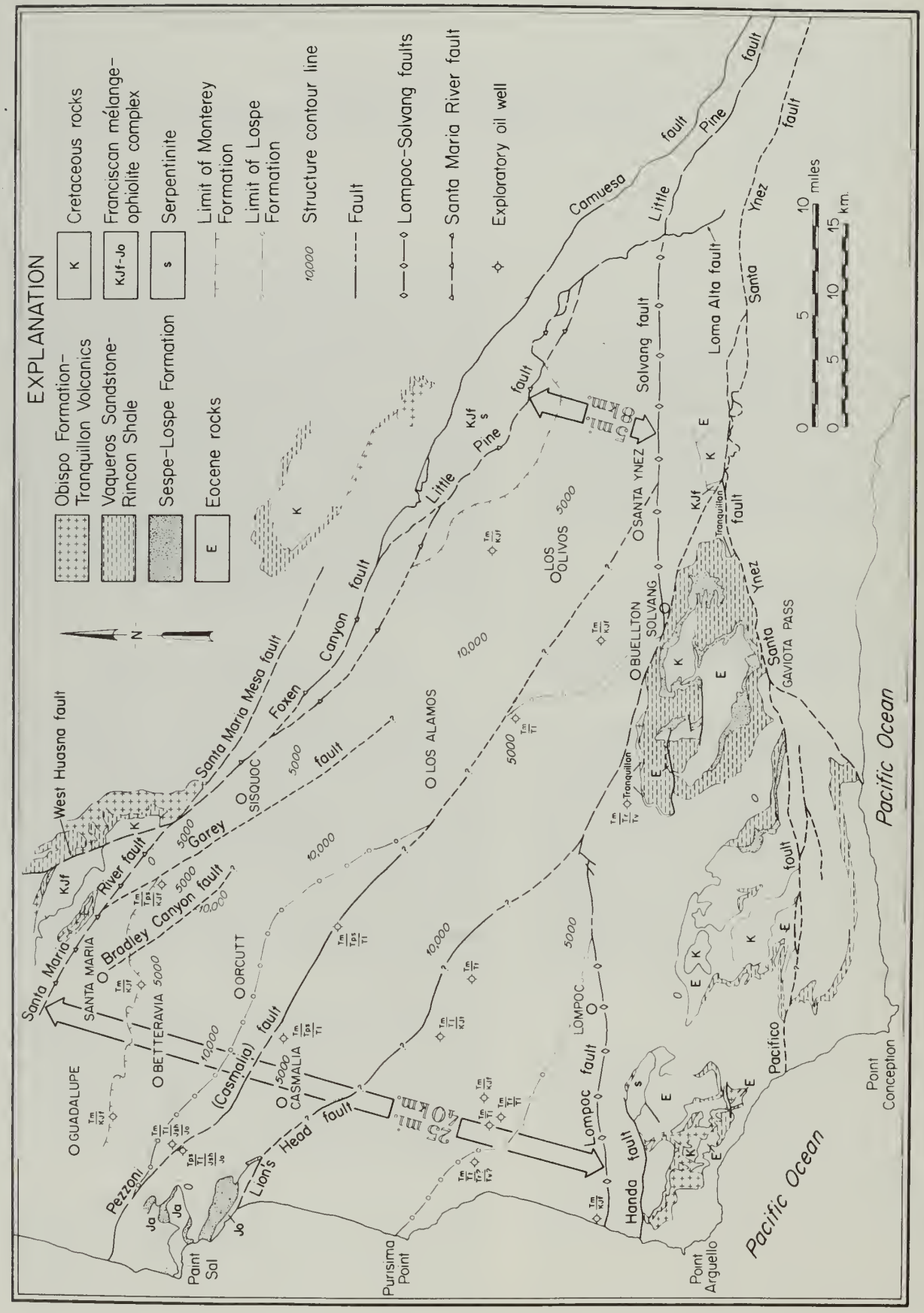

FIGURE 1. Generalized paleogealagic map (pre–Manterey Farmatian) and generalized structure cantaur map (base af Manterey Farmatian), San Luis Obispa and Santa Barbara Counties, Califarnia. Generalized distributian af selected stratigraphic units is fram Jennings (1959), and Hall (1977), recannaissance gealagic mapping in the Sisquac and Lampac areas, and fram care hale data supplied by the California Divisian af Oil and Gas, Santa Maria District Office. Incamplete well data fram well lags are shawn: Manterey Farmatian, Tm; Paint Sal Farmatian, Tps; "Temblar" Farmatian, Tt; Rincan Shale, Tr; Vaqueras Sandstane, Tv; Laspe Farmatian, Tl; Franciscan racks, KJf; Jurassic shale, Jsh; Jurassic aphialite, Ja. A. Sylvester (Univ. Calif., Santa Barbara) reparts (persanal cammunicatian, 1977) the presence af a fault in the vicinity af Santa Ynez and Salvang with a narthwest trend. I believe that this fault is a cantinuatian af the Pezzani fault and passes near Las Alamas; the exact lacatian, hawever, is unknawn.

Table 1. Generalized pre–Pleistocene stratigraphic sections from the margins of the Lompoc Santa Maria basin, western Santa Ynez Mountains (Dibblee, 1950), Santa Maria and Lompoc basins (Woodring and Bramlette, 1950), and the area north of the Santa Maria River (Hall, 1977), Santa Barbara County, California.

Age of rock units	*Western Santa Ynez Mountains*	*Santa Maria–Lompoc basin*	*Cuyama–Santa Maria–Sisquoc Rivers area*
Pliocene	—	Careaga Sandstone	—
Pliocene	—	Foxen Mudstone	—
Miocene–Pliocene	Sisquoc Fm.	Sisquoc Fm.	—
Miocene	Monterey Fm.	Monterey Fm.	Monterey Fm.
Miocene	L. Mont. Fm.	Pt. Sal Fm.	Pt. Sal Fm.
Miocene	Tranquillon Volcanics	—	Obispo Fm.
Oligocene–Miocene	Rincon Shale	—	Rincon Shale
Oligocene	Vaqueros Ss.	—	Vaqueros Ss.
Oligocene	Sespe/Alegria Formations	Sespe–Lospe Formations	Sespe Fm.
Oligocene	Gaviota Fm.	—	—
Eocene	Eocene rocks	—	—
Cretaceous	Cretaceous rocks	—	Cretaceous rocks
Jurassic	Honda Fm.	"Knoxville" Fm.	Jurassic shale
Cretaceous–Jurassic or Jurassic	Franciscan rocks	Franciscan rocks or ophiolite	Franciscan rocks

present in adjoining areas (figure 1), and Eocene rocks are present north and south of the Little Pine fault near the Loma Alta fault (figure 1), but absent in the subsurface in the vicinity of Santa Ynez, approximately 15 km to the west of the Loma Alta fault, and elsewhere in the basin between the Santa Maria River–Foxen Canyon fault (figure 1). These facts are difficult to explain by this hypothesis, unless one assumes that the Cretaceous or Eocene rocks were also eroded completely from a Franciscan topographic high. Also, subsurface data do not provide evidence of uneroded remnants of these units. Furthermore, if the wedge–shaped Santa Maria basin was a high during or following, for example, the time of deposition of the Vaqueros and Rincon in or surrounding the region and the deposition of the Obispo volcanic ash in a marine environment within the basin, it would require an unusual history for the basin. The events would have been: (a) the deposition of the non–marine Sespe–Lospe formations, (b) the deposition of the shallow–water marine Vaqueros Sandstone followed by the deep–water deposited Rincon Shale either surrounding the basin or within the basin, (c) the deposition of the Obispo tuff within a marine basin, (d) uplifting of the deep-water basin, with the Vaqueros, Rincon, and Obispo eroded away, and (e) then the down-dropping of the area almost simultaneously with the erosion of the Obispo Formation so that the deep-water Point Sal or Lower Monterey and Monterey Formations could be deposited in a deepening basin. Note that the base of the Monterey Formation is between 10,000 and 15,000 feet (3,048 to 4,572 m) below sea level (figure 1). Thus, a wedge-shaped high would have to persist from Oligocene to Miocene while the area surrounding the high would be subsiding, and the high-standing land mass would have to subside rapidly in the Miocene and Pliocene, to allow deep-water Point Sal, Monterey and Pliocene sediments to cover the supposed high-standing land mass.

Comparisons of lithologies and stratigaphic sections (table 1) tend to support the third model for the development of a Santa Maria–Lompoc pull–apart basin, although detailed stratigraphic and lithologic studies are yet to be made. In the western Santa Ynez Mountains the stratigraphic section is unlike that north of Santa Ynez Valley (Lompoc, Buellton, Santa Ynez, figure 1), but it agrees relatively closely with the stratigraphic section north of the Santa Maria River–Little Pine fault system nearly 45 km to the north (near Santa Maria, figure 1, table 1). The stratigraphic section in the western Santa Ynez Mountains (east of Point Arguello, figure 1) includes: (1) Franciscan mélange and Honda Formation (457 m), (2) Cretaceous rocks (2,743 m), (3) Oligocene and Eocene rocks (1,981 m), (4) Sespe–Lospe formation (91 m), (5) Vaqueros–Rincon units (213 m), (6) Tranquillon Volcanics (365 m), and (7) Monterey Formation (914 m). The Tranquillon Volcanics are the same age as the Obispo Formation (Tranquillon Volcanics: 17 ± 1.2 (basalt), 16.8 ± .5 (tuff), 16.1 ± .6 (tuff) m.y.; Obispo Formation: 15.3 ± .9, 16.3 ± .5, 15.4 ±.5, 15.3 ±.5, 16.5 ± .8 m.y.; Turner, 1970). This sequence of rocks does not correspond exactly with that on the north side of the basin, north of the Santa Maria River fault. A reconstruction of the Tertiary geologic history of the region prior to the pulling apart of the basin is required to understand why exact correlations cannot be made.

A generalized possible Tertiary history of the development of the Santa Maria–Lompoc basin could be as follows. Figure 2a shows a generalized paleogeologic map after the deposition of the Gaviota Formation of Oligocene age and older rock units (Cretaceous, K; Eocene, E). Before deposition of the non–marine Sespe Formation there could have been strike–slip along the inferred fault as shown in Figure 2b (diamonds). Later, oblique rifting along this fault (post Obispo, post figure 2d time) would account for the development of the Santa Maria–Lompoc basin. The inferred fault (diamonds) is called the Lompoc–Solvang fault (figure 1). Its inferred presence is supported by the fact that north of its approximate location the stratigraphy (known from exploratory oil wells) is markedly different from that south of the inferred fault. Figure 2c depicts a generalized paleogeologic map before the deposition of the Monterey Formation. Sespe–Alegria formations (in part Lospe Formation), Vaqueros Sandstone, Rincon Shale, and Obispo–Tranquillon volcanic rocks

unconformably overlie the Franciscan rocks (F), Cretaceous rocks (K), Eocene rocks (E), and Oligocene (Gaviota Formation) rocks (O) (F, K, E, and O shown as dotted and buried contacts). The fault (diamond) was either buried or was continuously or sporadically active during the deposition of the Tertiary rocks shown in Figure 2c. Subsequently, a series of pull–apart basins may have developed along the present coastal part of central California, one such basin being the Santa Maria–Lompoc basin. The Santa Maria–Lompoc basin was probably later transected by the San Simeon–Hosgri fault zone (Hall, 1975a).

After deposition of the Obispo–Tranquillon volcanic rocks, the formation of the Santa Maria–Lompoc basin (figure 2d) began with the development along the right–slip transform Lompoc–Solvang–Santa Maria River–Foxen Canyon–Little Pine fault system, or there was renewed movement along this already extant fault system, possibly during the Luisian Age (14 m.y.b.p.). The margins of the basin were formed by the Lompoc –Solvang fault (diamonds), or pull–apart shoulder, and the Santa Maria River–Little Pine fault (triangles), or pull–apart shoulder. Right–slip along the fault probably accompanied dip–slip and the late Miocene and Pliocene seas flooded the deepening basin. Note that near Los Alamos the base of the Monterey Formation is nearly 4,572 m (15,000 feet) below sea level (figure 1), that the maximum subsurface thickness of the Monterey Formation is probably more than 1,524 m (5,000 feet), and that maximum outcrop thickness at the margins of the basin is approximately 655 m (2,150 feet). It is suggested that the Santa Maria River and Lompoc-Solvang faults are part of the same transform right-lateral fault system and were probably a single fault or fault zone before the late Miocene pull-apart which produced the Santa Maria-Lompoc basin.

The formation of the late Tertiary pull–apart basin, with motion vectors of extension parallel to the strike–slip faults, began following the deposition of the Obispo (Tranquillon) Formation, probably during the middle Miocene (14 m.y.b.p.). Walls along the fault margins may have begun to sag and pull apart as early as the early Oligocene, or even earlier if there was more than one episode of rifting. The Franciscan rocks are weak, easily folded, faulted, and stretched, and subject to tectonic brecciation. What occurred to the deeper crustal layers is unknown, but there was not massive extrusion. During the opening of the basin only minor volcanic flows or intrusions (e.g., those near Point Sal) occurred contemporaneously with the pull–apart and the stretching of the Franciscan mélange. Rotational movement (figure 2e) or bending accompanied formation of the pull–apart basin. This movement resulted in a change of trend of the Lompoc–Solvang fault (figure 2d) from northwest to east–west (figure 2e). The rotation or bending would account for the distribution of the Cretaceous (K), Eocene (E), and Oligocene (O) rocks south of the inferred Lompoc–Solvang fault and may have played a role in the general development of the Transverse Ranges. The amount of counter–clockwise rotation is reduced if the Lompoc–Solvang fault initially had a more westerly trend. The maximum pull–apart is between 40 and 50 kilometers.

Because of probable strike–slip along the Lompoc–Solvang–Santa Maria River–Little Pine faults, the Cretaceous and Eocene rocks, Gaviota Formation, Vaqueros Sandstone, Rincon Shale, and Obispo–Tranquillon volcanic rocks near Point Arguello probably were in closer juxtaposition initially with rocks of the same lithology and ages at the latitude of Camuesa fault (figure 1) or near Zaca Lake (Jennings, 1959) than with rocks near the Santa Maria River fault. That is, the rocks south of Lompoc and Solvang in the Transverse Ranges moved along a right–slip transform Lompoc–Solvang–Santa Maria River–Little Pine fault, the basin opened along this fault,rotation or bending occurred, and the Lompoc–Solvang fault and rocks south of the fault were brought into their present positions. Left–slip occurred at a later time along a Santa Ynez–Pezzoni fault system (partially shown in figure 1).

Following the deposition of the late Tertiary sediments (Sisquoc, Foxen, Careaga formations) within the deepened basin, a part of the basin was moved more than 80 km to the north along the San Simeon–Hosgri fault zone (Hall, 1975a). It is unlikely that the slip is less than 80 km because the package of rocks in the Santa Maria region (i.e., Jurassic ophiolite, chert, and shale, Lospe Formation, Monterey Formation, and Pliocene rocks) which were moved north along the San Simeon–Hosgri fault zone has a distribution limited to the Santa Maria basin. At its widest point the basin is about 50 kilometers (30 miles) wide. However, distributions of the Jurassic ophiolite, chert, shale, and Lospe Formation, and associated younger rocks that crop out near Point Sal are known from the subsurface in an area of less than 19 km (12 miles). The distance between Point Sal and the San Simeon area (figure 3) is more than 100 km (62 miles) and the diameter of the unique package of rocks in the Santa Maria area is less than 20 km, thus the offset would be at least 80 km, and more likely 95 km. The releasing half bend, depicted at the southeast end of the pull–apart basin in Figure 2d, would have had a mirror image at the northwest end, but this has been truncated by the San Simeon–Hosgri fault and is now 100 km to the north at San Simeon (figure 3). The Pliocene Careaga Sandstone at San Simeon suggests that the 80 to 95 km of right–slip along the San Simeon–Hosgri fault occurred during the last 5 m.y. The earliest strike–slip movement along the San Simeon–Hosgri fault would probably have occurred 9 to 13 m.y. ago. Clearly all movement took place along the fault following the formation of the pull–apart structure.

Some investigators have suggested that the offshore exploratory well, Standard–Humble #1 (figure 3), contains a section of rocks that is most like that onshore at or near the same latitude (Santa Maria Valley). The offshore well encountered the following sections: top of the Sisquoc at 3,402 ft (thickness 635 m, or 2,082 ft); top of the Monterey at 5,484 ft (thickness 358 m or 1,176 ft); top of the volcanic ash (probably Obispo–Tranquillon volcanics) at 6,660 ft (thickness 122 m, or 400 ft); and top of "volcanic rocks" (probably Lospe, David Howell, personal communication, 1977) at 7,060 ft (bottom of well at 7,797 ft). Onshore, at or near the same latitude, well data (Woodring and Bramlette, 1950, cross section A–A') provide information to show that the Monterey Formation lies either on the Lospe or directly on Franciscan rocks, whereas the well probably contains volcanic ash of the Obispo or Tranquillon volcanic rocks.

Continuous or renewed late Tertiary or Quaternary movement must have occurred along the Santa Maria River fault. Evidence for this suggestion is provided by the geology in the Twitchell Dam quadrangle (Hall, 1977) and the geomorphology and late Tertiary and Quaternary geology along the Foxen Canyon fault (figure 1). In the Twitchell Dam quadrangle the West Huasna fault cuts Quaternary deposits and is in turn truncated by, or is the same age as, the Santa Maria River fault.

OTHER NEARBY REGIONAL BASINS

The Morro Bay basin to the north of the Santa Maria basin (50 km north of Santa Maria) shows similar relationships to the development of the Santa Maria basin. Although the correlation

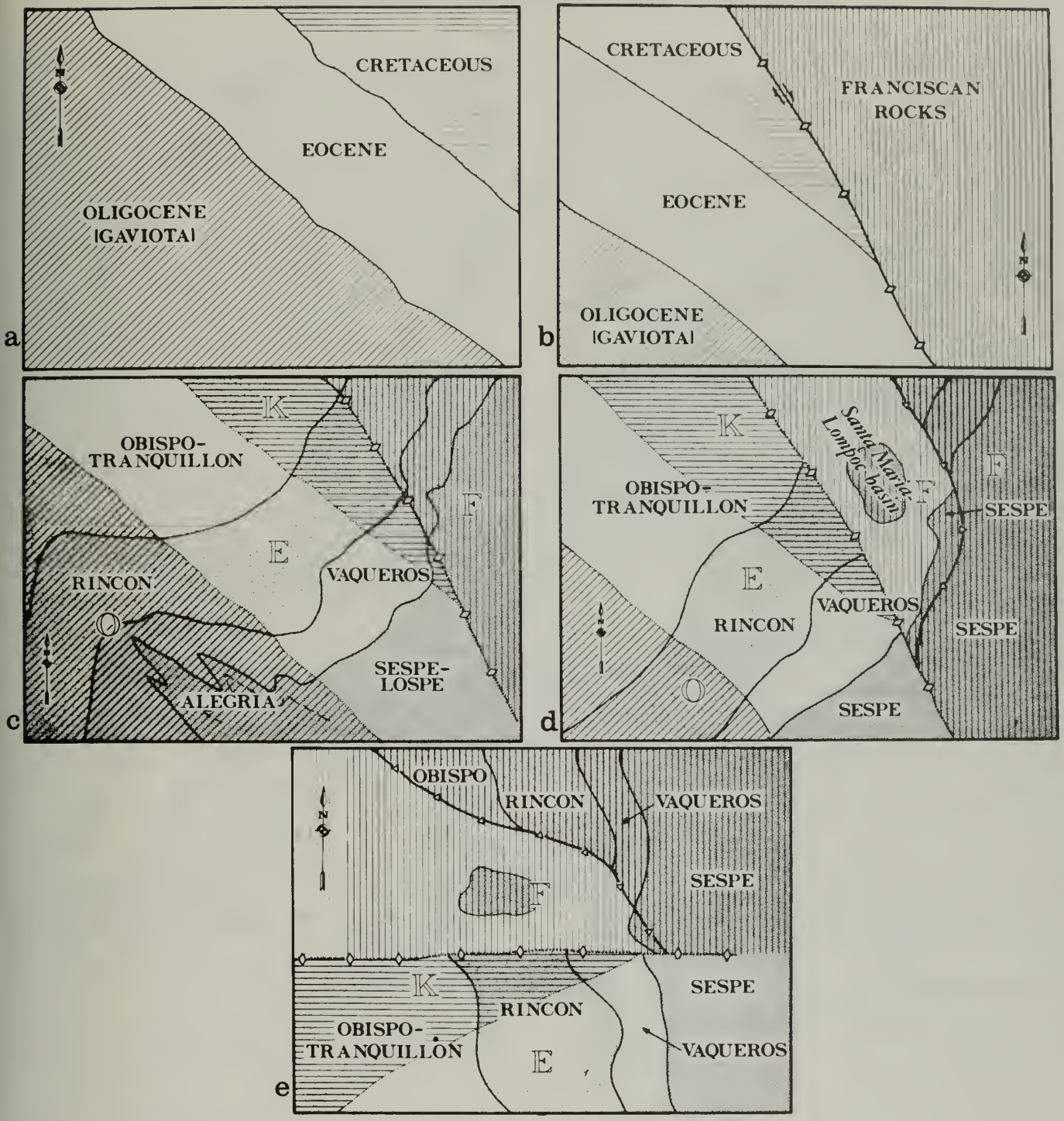

FIGURE 2. Hypotheticol poleogeologic mops.

2o. Hypotheticol poleogeologic mop following or during the deposition of the Govioto Formation of Oligocene oge. Coostol port of Californio.

2b. Hypotheticol poleageologic mop, following strike–slip olong the Lompoc–Solvong–Little Pine foult ond before the deposition of the Sespe–Lospe formotions. Coostol port of Californio in the vicinity of whot is now northwestern Sonto Borboro County. The initiol trend and amount of strike–slip is not known.

2c. Hypotheticol poleogeologic mop following deposition of the Obispo–Tronquillon volconic rocks. Follawing deposition of the Govioto Formotion and strike–slip on the Lompoc–Solvong foult, the Sespe (ond the morine equivolent Alegrio) (coorse swirled dots), Voqueros (fine rondom dots), Rincon ond Obispo–Tronquillon rocks (fine mixed dots) were successively (northeost–southwest trend) ond uncanformobly deposited upon the underlying Fronciscon (F) (verticolly ruled), Cretoceous (K) (horizontolly ruled), Eocene (E) (no pottern), ond some Oligocene (O) (diogonolly ruled) rocks.

2d. Hypotheticol poleogeologic mop showing geology of northwestern Sonto Borboro County opproximotely 14 m.y.b.p. Bosin pull–aport begon to develap olong the Lompoc–Solvong–Little Pine foult contemporaneously with the birth of the Sonto Morio River–Foxen Conyon–Little Pine foult zone. Vaqueros, Rincon, ond volconic rocks ore ot the morgins of the opening bosin, but ore removed, except for remnonts left on the stretched ond tectonicolly mixed Fronciscan rocks, from the center of the bosin. Cretoceous, Eocene, ond Oligocene rocks olong with the overlying Sespe, Vaqueros, Rincon ond Obispo–Tronquillon rocks ore southwest of the Lompoc–Solvong–Little Pine fault zone (diomonds); Fronciscon ond remnonts of the Sespe rocks lie between the two foults, ond Cretoceous, Sespe, Voqueros, Rincon, and Obisoo rocks lie northeost of the Sonta Morio River–Foxen Conyon–Little Pine foult zone (triongles). Strike–slip probobly occomponied the development of the pull–aport bosin.

2e. Generolized pre–late Miocene poleogeologic mop. The proposed model suggests the counterclockwise rototian of the Lompoc–Solvong–Little Pine foult, rototion thot hos occurred some time since the lote middle Miocene. The inferred Lompoc–Solvong foult in the proposed model is the northern boundory of Tronsverse Ronges in the western port of Santo Borboro County.

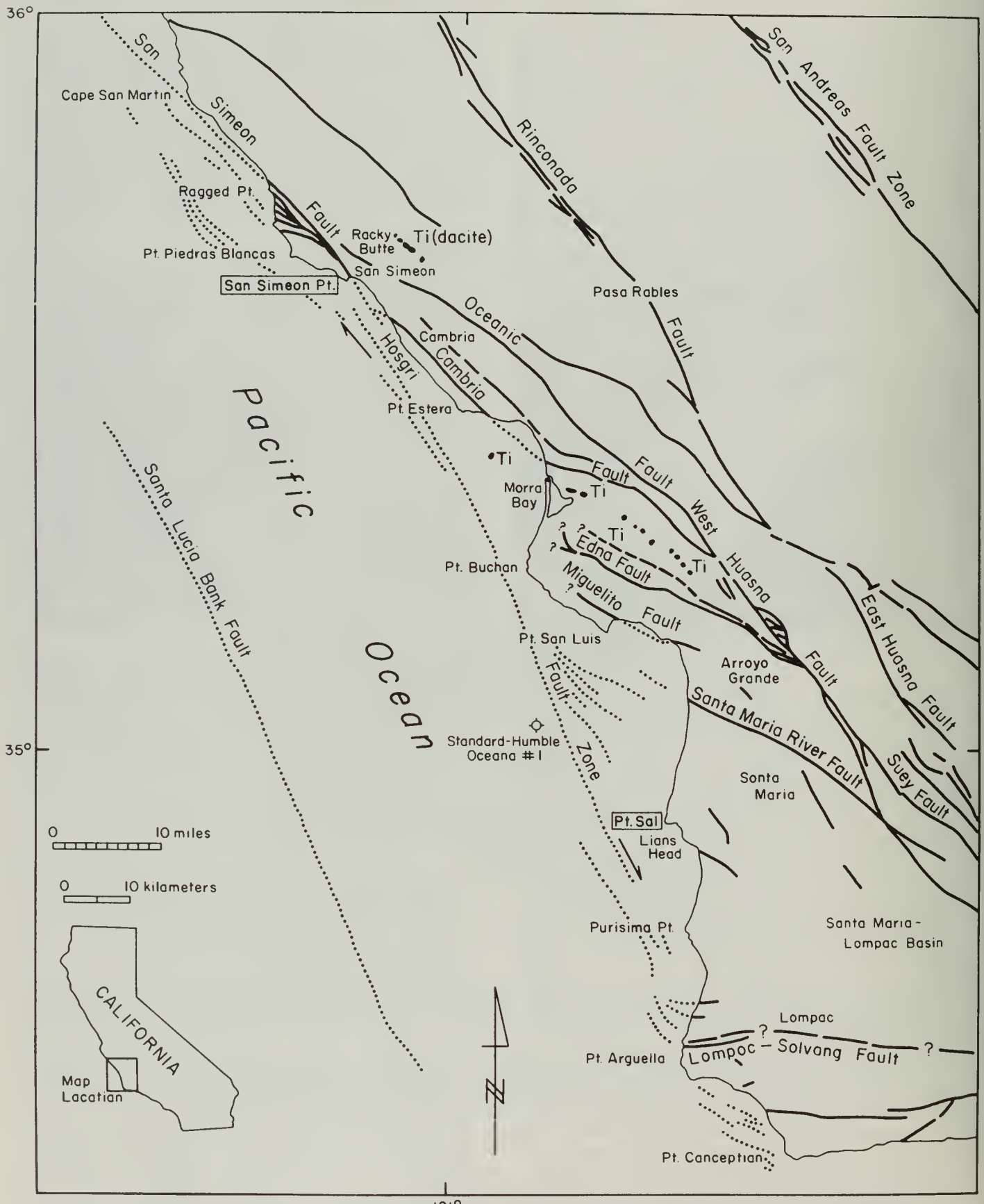

FIGURE 3. Lacatian af the San Simean–Hasgri fault zane, Santa Maria River, Lompac–Salvang, and ather faults. Spats (Ti = Tertiary intrusive) indicate sites af Oligacene hypabyssal valcanic racks, including the Marra Rack–Islay Hill valcanic racks and similar racks in the narth near Racky Butte. Lacatian af Standard Oil Ca. af Califarnia–Humble Oil Ca. "Oceana # 1" is shawn west af San Simean–Hasgri fault system.

of rocks at the margins of the Morro Bay Tertiary basin is not as clear as those at the margins of the Santa Maria–Lompoc basin, the Morro Bay basin might also represent a pull–apart structure. The basin may have begun to open during the early Oligocene and the dacite–felsite rocks of that age, which form Morro Rock and 12 or 13 other major intrusive masses in the area (including the Cambria Felsite), may reflect a period of volcanism and intrusion at depth during basin opening. Such an interpretation would have to account for the fact that the rifted intrusive rocks were dacitic and not basaltic rocks. Equally as speculative is the suggestion that the Morro Rock–Islay Hill complex (Ernst and Hall, 1974) was rotated 10 to 15 degrees to the west after emplacement, and that the Cambria Felsite in Cambria and at Rocky Butte (Hall, 1973, 1974, 1975b; Hall and Corbató, 1967; Hall and Prior, 1975) were aligned with the Morro Rock–Islay Hill complex at the time of emplacement during the Oligocene. An alternative explanation for the Morro Bay basin is that it is an uplifted, tipped faulted wedge basin (see Crowell, 1974) bounded by the Pismo and Huasna inclined subsidence basins. Such a suggestion does not preclude pre–mid– or late–Miocene counterclockwise rotation. If the Morro Bay basin is an uplifted tipped basin, it must have subsided during late Miocene or Pliocene time, because remnants of rocks of these ages are present within the regions bounded by the Edna–Los Osos Valley and West Huasna fault systems. These faults form the margins of the Morro Bay tipped fault wedge basin.

SUMMARY

Based on the geology, stratigraphy, distribution of sedimentary and volcanic rocks, and lithologic similarities of widely separated rock types, there is evidence to support the hypothesis that the Santa Maria–Lompoc basin is a pull–apart structure. The fault–bounded basin is wedge–shaped with the maximum pull–apart being nearly 50 km. The basin may have undergone recurrent periods of rifting, perhaps during the deposition of the Rincon Shale, the most recent of which took place approximately 14 m.y.b.p. The present location and orientation of the Cretaceous to middle Miocene rocks in the western Transverse Ranges are due to right slip along the Lompoc–Solvang–Santa Maria River–Little Pine right–lateral transform, subsequent counterclockwise rotation or bending of the region, and late Tertiary and Quaternary left slip along the Santa Ynez fault.

Other basins in the region, e.g. Pismo and Huasna, are possibly tipped subsidence basins (Crowell, 1974), and the Morro Bay basin is a tipped fault wedge basin (Crowell, 1974). All structural basins were probably formed between large strike–slip faults during late middle or late Miocene and were, in part, later affected by movement along such faults as the San Simeon–Hosgri fault zone and the Rinconada fault (Dibblee, 1976). There has apparently been at least 80 to 95 km of right slip along the San Simeon–Hosgri fault zone since the Pliocene (during the last 5 m.y.) and following the formation of the Santa Maria–Lompoc pull–apart basin.

Acknowledgments

I wish to thank J. C. Crowell, W. G. Ernst, W. R. Dickinson, and Eli Silver for their helpful comments and discussions of the concepts expressed in this paper.

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MORPHOLOGY, RECENT ACTIVITY, AND SEISMICITY OF THE SAN GREGORIO FAULT ZONE

By Kevin J. Coppersmith and Gary B. Griggs*

Abstract

The Son Gregorio is o complex foult zone up to 3 km wide composed of several onastamasing and subparallel traces. A number of troces exhibit late Pleistocene and Halocene offsets. The fault is ossocioted with recent seismicity. First-motian analysis shaw these earthquakes in generol to be due to regionol right sheor ond compressianal stress. Limited field investigotions ond triangulotion survey doto show no sign of foult creep ar strain accumulation olong the onshare portion af the fault zone.

INTRODUCTION

In 1968 the San Francisco sheet of the State Geologic Map showed the San Gregorio fault zone essentially as a single fault trace 52 km long. Today we are entertaining the possibility of a fault zone over 420 km long extending south from Bolinas to Pt. Arguello. Numerous investigations have focused on this feature over the past 9 years and a vast amount of both onshore and offshore data have been collected. Much of this study was precipitated by the initial construction of a nuclear power plant at Diablo Canyon in San Luis Obispo County and a proposal for a nuclear plant at Davenport in northern Santa Cruz County. The Diablo Canyon plant lies near the Hosgri fault, which was discovered in 1971, and the proposed Davenport site was located within a mile of the offshore portion of the San Gregorio fault zone.

The portion of the San Gregorio fault on shore has long been recognized as an important break that separates a section of upper Tertiary sedimentary rocks abutting and overlapping a granitic highland to the east from a section of younger Tertiary rocks overlying Cretaceous sedimentary rocks to the west (Jahns and Hamilton, 1971).

In California emphasis has been placed primarily on the San Andreas fault, but continued research has indicated that numerous other faults in the San Andreas system are active** and potentially hazardous as well. The San Gregorio fault clearly falls into this category, but future land-use planning and hazard assessment are problematic along it due to difficulties in assessing recent activity. In order to make a reasonable and substantive assessment of a fault's activity, which is necessary in the siting of critical structures, comprehensive information on all aspects of its past behavior must be analyzed.

This paper focuses briefly on new aspects of seismicity patterns and strain accumulation and attempts to integrate these with existing data on the known distribution and character of fault traces. The tectonic context is considered elsewhere (Graham and Dickinson, 1977; Greene, 1977; Silver, 1977; Weber and Lajoie, 1977) and will not be discussed here.

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**An active fault is here defined as a fault within a spatial and temporal tectonic regime such that movement can be expected in the future.

DISTRIBUTION OF FAULT TRACES

The complexity of a fault zone should be considered in assessing the potential for future movement along individual traces. In a world-wide study of strike-slip faults, Bonilla (1970) found that subsidiary faults (branch and secondary) showed far less movement than primary traces in many areas. Therefore, studies of fault activity often attempt to determine which traces are primary and, as such, are probably most active. Frequently, however, structural complexities such as *en echelon* faulting preclude a reasonable differentiation between primary and subsidiary traces.

In general, the San Gregorio is now recognized as a very complex fault zone up to 3 km wide consisting of a number of subparallel fault traces (figure 1). Detailed mapping by Weber (1977) has shown the San Gregorio fault in southern San Mateo County to consist of up to eight traces, whereas only two were previously mapped. The seismic profiling of Greene (1970) and Greene and others (1973) within Monterey Bay shows a complex zone over 15 km wide.

The San Gregorio seems to form the western edge of a zone which consists of numerous discontinuous fault traces (figure 1). Offshore seismic work by Alpine Geophysical Associates (1971) indicates 3 or 4 traces extending southeastward from Point Año Nuevo. The complexity of the fault zone, as revealed in all of these studies, however, often makes it difficult or impossible to identify a "main" trace whose activity can be considered greater than the branch or secondary faults.

RECENCY OF FAULT MOVEMENT AND HISTORY OF RECURRENT MOVEMENT

Recency of movement generally is the most readily discernible aspect of fault activity, and investigation of recency of movement is probably the most widely applied technique in fault activity assessment (Ziony and others, 1973). The basic assumption is that the fault traces which moved last will most likely move next.

Geologic mapping and subsurface exploration in the northern Santa Cruz Mountains have delineated the early history of the San Gregorio fault and indicate that mid-Tertiary displacements must have had a large vertical component (see Clark and Brabb,

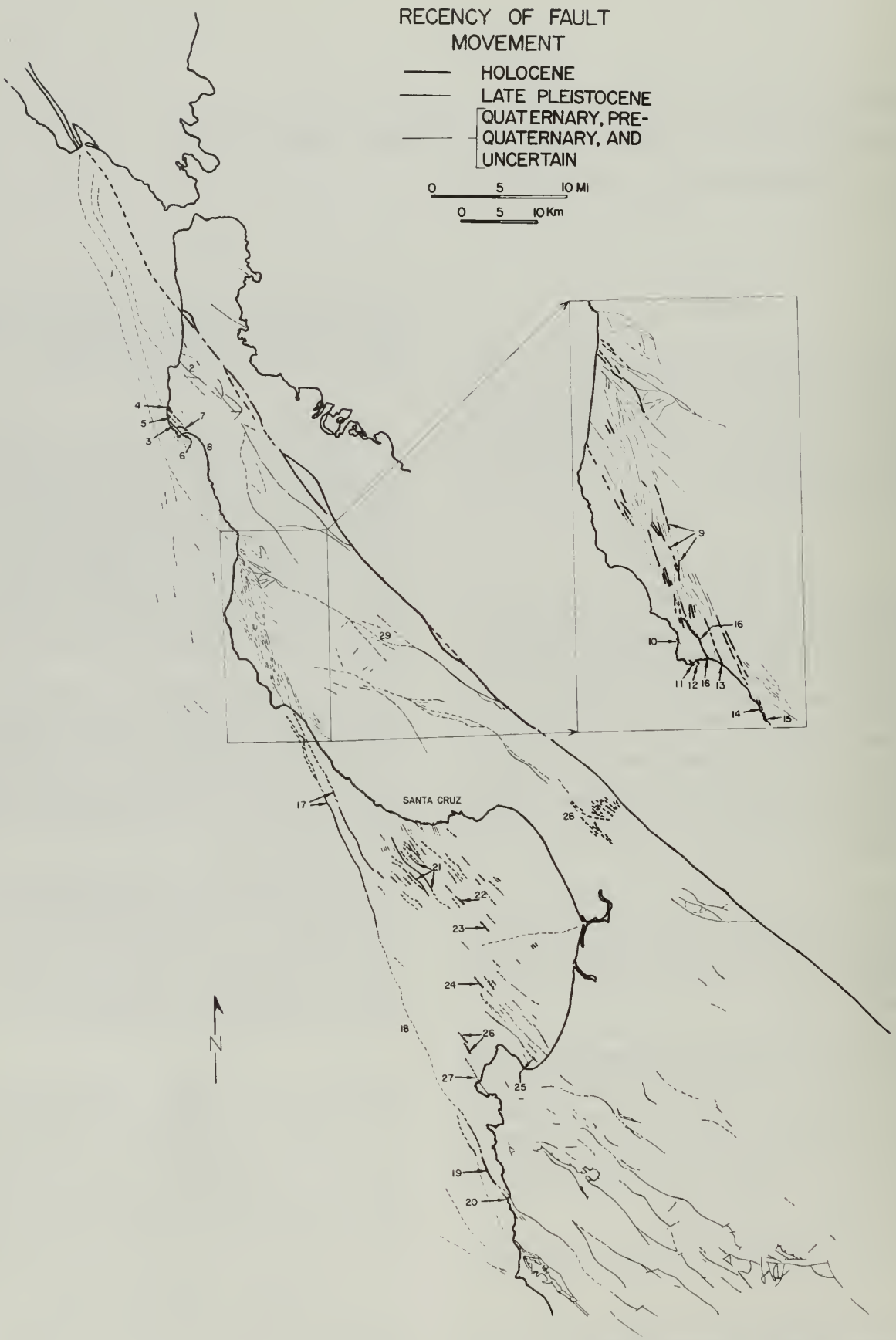

FIGURE 1. Fault map shawing currently recagnized fault traces. Nate the camplex nature af the fault zane. Numbers refer ta Table 1 which summarizes infarmatian an recency af fault mavement. Sources are alsa given. Dashed lines indicate discontinuaus ar inferred traces.

1977). Recent work (see Graham and Dickinson, 1977) indicates significant right–lateral strike–slip offset.

The evidence for recent movement along the San Gregorio fault, based solely on observed displacements and fault–controlled geomorphology, is summarized in Table 1, with locations identified in Figure 1. Some of the first indications of more recent movement along the San Gregorio fault zone were from the observations of Pleistocene marine terrace offsets along the Seal Cove trace (Glenn, 1959; see location 3 on figure 1). Continuing field investigations to the south have pinpointed numerous other marine terrace offsets. A total of eight traces of the San Gregorio fault zone have offset the first marine terrace (120,000 ± years B.P.) in southern San Mateo County (Weber and Lajoie, 1977). In addition, recurrent fault movement is indicated by progressively greater northward tilting of the uplifted terraces with increasing elevation and age (Lajoie *et al,* 1972). Vertical offsets along some traces are large enough that more than one episode of movement can be inferred.

A fault trace exposed in the seacliff near Pt. Año Nuevo (location 11 in figure 1) thrusts the Miocene–age Monterey Shale over terrace and fluvial deposits of the first marine terrace (figure 2). The wave cut platform is displaced about 5.2 meters, and about 7.9 meters of dip separation has occurred. The exposed section has been carefully examined and the structural and stratigraphic relationships seem to indicate at least three episodes of movement along this fault trace over about the last 120,000 ± years. One shear surface is truncated by a second, which in turn is cut by still a third, more recent shear surface.

The offset of fluvial features, including an alluvial fan (location 7 on figure 1) is evidence for Holocene offset along the Seal Cove trace (Lajoie *et al,* 1972). Steeply dipping fluvial deposits exposed in the seacliff east of Pt. Año Nuevo (location 16 on figure 1) dated by C^{14} at 9510 ± 140 years have also been offset (Weber and Lajoie, 1974).

Southeast of Pt. Año Nuevo, late Pleistocene offsets on the seafloor have been documented (Greene *et al,* 1973), but within Monterey Bay seismic profiling has delineated displacement of the seafloor, indicating probable Holocene activity on the Monterey Bay fault zone (Greene *et al,* 1973, locations 22–26, figure 1).

STRAIN ACCUMULATION OR CREEP

Fault creep has not yet been observed or measured along traces of the San Gregorio fault zone. Field mapping investigations to date have not discovered evidence of off–set cultural features (Weber and Lajoie, personal communication, 1977), but detailed or systematic studies have not been made. The installation of creepmeter or alignment arrays across individual traces may help confirm or deny creep along the fault.

All existing U.S.Coast and Geodetic Survey triangulation–survey data in the onshore San Gregorio area were interpreted for evidence of strain accumulation and/or fault slip. Those stations and directions which were resurveyed at least once are shown in Figure 3. Frank's (1966) method was utilized for the only triangle that has been resurveyed in this area (Road–Lane–Buetro 2), and no statistically significant strain or slip was detected during the 16-year period 1931–1947. Because the triangulation precision is only second order (one part in 50,000) and most of the time periods are relatively short, this data is probably not capable of showing strain rates comparable to the long–term geologic rate of fault offset of about 1.6 cm/year (Weber, oral communication). Resurveying these stations, however, would provide an additional 30 years of record to most of the triangulation data and may give significant results. In addition, strainmeter and line–length surveys could prove useful in estimating strain accumulation.

Seismicity Patterns

The spatial association of historic earthquakes with identified faults can be a strong indicator of activity, even when no good evidence of recent ground displacement can be found. Several large historic earthquakes occurred within the San Gregorio fault zone area before the time of more accurate epicenter locations (Griggs, 1973). Two earthquakes with Rossi–Forel intensities of VIII and Richter magnitudes of 6, occurred about an hour apart during October 1926. These were located somewhere in Monterey Bay and were felt over an area of more than 100,000 square miles (Mitchell, 1928).

In recent years, the National Center for Earthquake Research (NCER) of the U.S. Geological Survey has established an array of seismographs that provides accurate monitoring of seismic activity along the Santa Cruz–San Mateo County coastal area and in Monterey Bay. A plot of recent seismicity shows concentrations of epicenters along two different portions of the San Gregorio fault zone (figure 4). A number of earthquakes, primarily of magnitudes 2 to 4, have occurred in the coastal and offshore area between the San Andreas and San Gregorio faults west of San Francisco. Movement on either of these zones, and/or the Pilarcitos fault between them, may have generated these shocks. Very few epicenters have been located along the onshore portion of the fault. Southeast of Año Nuevo Point and extending across Monterey Bay, a number of small to moderate–size epicenters have been plotted (figure 4). The main cluster of earthquakes occurs in the middle of the Bay and consists of about 20 events, the largest of which ($M = 4.6$) occurred in 1971. Many of the larger earthquakes in this cluster occurred in 1971, but shocks have also been recorded as recently as July 2, 1978 ($M = 3.5$). A swarm of over 20 earthquakes ($M \geqq 1$), the largest with $M = 2.5$, occurred on the Monterey peninsula between December 1975 and February 1976. Movement on the Cypress Point fault may have caused the earthquakes, but field investigations after the swarm showed no good evidence of ground–surface displacement (Greene, 1977, oral communication).

A longitudinal cross section of hypocenters has been constructed indicating the distribution of post–1961 earthquake foci with depth along the projected surface of the San Gregorio fault (figure 5). The pre–1969 focal depths (represented by rectangles in figure 5) were only given within a particular range (e.g. 0–5 km, 6–10 km, etc.); therefore, the concentration of foci at a particular depth for this period is not realistic. The cluster of epicenters at the center of Monterey Bay seen in map view is also concentrated along the projected fault surface at depth. The average focal depth is about 8 km. This clustering may be indicative of a "slip–patch" (Wesson and others, 1973; Bufe and Harsh, 1976), an area of difficult slip along a fault surface where recurrent earthquake activity can be expected.

Several fault–plane solutions were calculated for earthquakes occurring within the last six years (figure 6). Solution quality is a function of the number and distribution of stations as well as the ability of the solution to explain the first–motion data. In general, the highest quality solutions show regional right–lateral shear with a component of compressional stress. Most solutions

Table 1.

No. on Map	*Fault name*	*Recency of movement*	*Evidence*
1	unnomed (Bolinos to Moss Beoch)	Mid–upper Pliocene (possibly Pleistocene)	Seismic profiling ond continuotion of on-shore rock types; no troces disploce seo floor (Cooper, 1973).
2	PILARCITOS	Quoternory (possibly Pleistocene or Holocene)	Quoternory displocement (Cummings, 1968); Pleistocene terroce north of foult is tilted southword but uplift hos occurred south of the foult in the Montoro Mountoin oreo; foult–controlled geomorphology (Smith, 1960; Borcherdt, 1975).
3	SEAL COVE moin troce	Holocene (?)	Foult–controlled geomorphology (Glenn, 1959; Jock, 1968; Lojoie *et al,* 1972).
4,5,6		Lote Pleistocene (80–120,000 yrs) (possibly eorly Holocene)	Offset of first morine terroce (Jock, 1968) ond possibly overlying fluviol deposits which hove been groded to o lower seo level (Lojoie *et al,* 1972).
5		Holocene (?)	Foult–controlled geomorphology (Lojoie, 1977, personol communicotion).
7		Holocene	Alluviol fon verticolly offset one meter (Lojoie, *et al,* 1972).
8		Lote Pleistocene (80–120,000 yrs)	Worping of Holf Moon Boy terroce (Lojoie *et al,* 1972).
9	SAN GREGORIO severol troces	Holocene (?)	Foult–controlled geomorphology (Weber, 1977); tilting of recent fluviol surfoces (Adom, 1975).
10–15		Lote Pleistocene (80–120,000 yrs)	First morine terroce offset verticolly 2–6 m (Weber, 1977, orol communicotion; Clork, 1970); most terroces tilted to the north (Lojoie *et al,* 1972). At Molino Heodlond to the south, first terroce offset is believed due to londsliding (Johns ond Homilton, 1971).
15		Lote Pleistocene (40–60,000 ? yrs)	Alluvium overlying terroce deposits cut by foult (Weber, 1977, personol communicotion).
16		Holocene	Offset of terroce deposits ond overlying soil seen in trench (Weber, 1977, personol communicotion). Steeply dipping fluviol deposits doted by C^{14} ot 9,510 ± 140 yeors hove been offset (Weber ond Lojoie, 1974).
17	OFFSHORE SAN GREGORIO	Lote Pleistocene Holocene (?)	Two troces come to within 6 m of the seo floor (bose of the bubble pulse) but don't oppeor to disploce seo floor (Greene *et al,* 1973). Three troces identified south of Año Nuevo (Alpine Geophysics, 1971).
18		?	Foult extended ocross Monterey Conyon bosed on lineor bottom topogrophy; not recognizoble in seismic profiles (Greene *et al,* 1973; Hoskins ond Griffins, 1971).
19	CARMEL CANYON	Holocene (?)	Seo floor disploced 2 m down to the west; dredging shows some Miocene sediments on either side of the foult so scorp is probobly not due to differentiol erosion (Greene, 1977, personol communicotion).

continued....

Table 1 (continued).

20	PALO COLORADO	Pleistacene (?)	Traces appear ta cut a Pleistacene wavecut plotfarm and passibly averlying Pleistacene ond Holacene depasits; anland Pala Calarada is narrow ond withaut clear fault–cantralled geamarphalagy (Greene *et al,* 1972; Greene, 1977, persanal communication).
21	MONTEREY BAY fault zane several traces	Pleistacene – Halacene (?)	Severol traces cut ta within 6 m af the sea floor (base af the bubble pulse) (Greene *et al,* 1973); na traces appear ta affset the first marine terrace in seacliff (Harding and Lawsan, 1976).
22–26		Halacene (?)	Sea–flaor displacement (Greene *et al,* 1973).
27	CYPRESS POINT	Pleistacene	Seismic prafiles show foult cuts Pleistacene depasits (Greene *et al,* 1973); anshare na gaad evidence af Quaternary affset ar fault –cantralled geamorphology (Greene, 1977, personal cammunicatian).
28	ZAYANTE–VERGELES	Halacene (?)	Fault–cantralled geamorphology ond affset Pleistacene–Holacene fluvial depasits (Dupré, 1975; Cappersmith, 1977, unpublished data).
29	BUTANO	Quoternary (?)	May be the baundary far Quaternary stream terrace depasits alang Pescadero Creek (Brobb and Pampeyan, 1972; Holl, *et al,* 1974); moy shaw fault–cantralled geamarphology near junctian with San Gregaria (Weber, 1977, persanal communicotian).

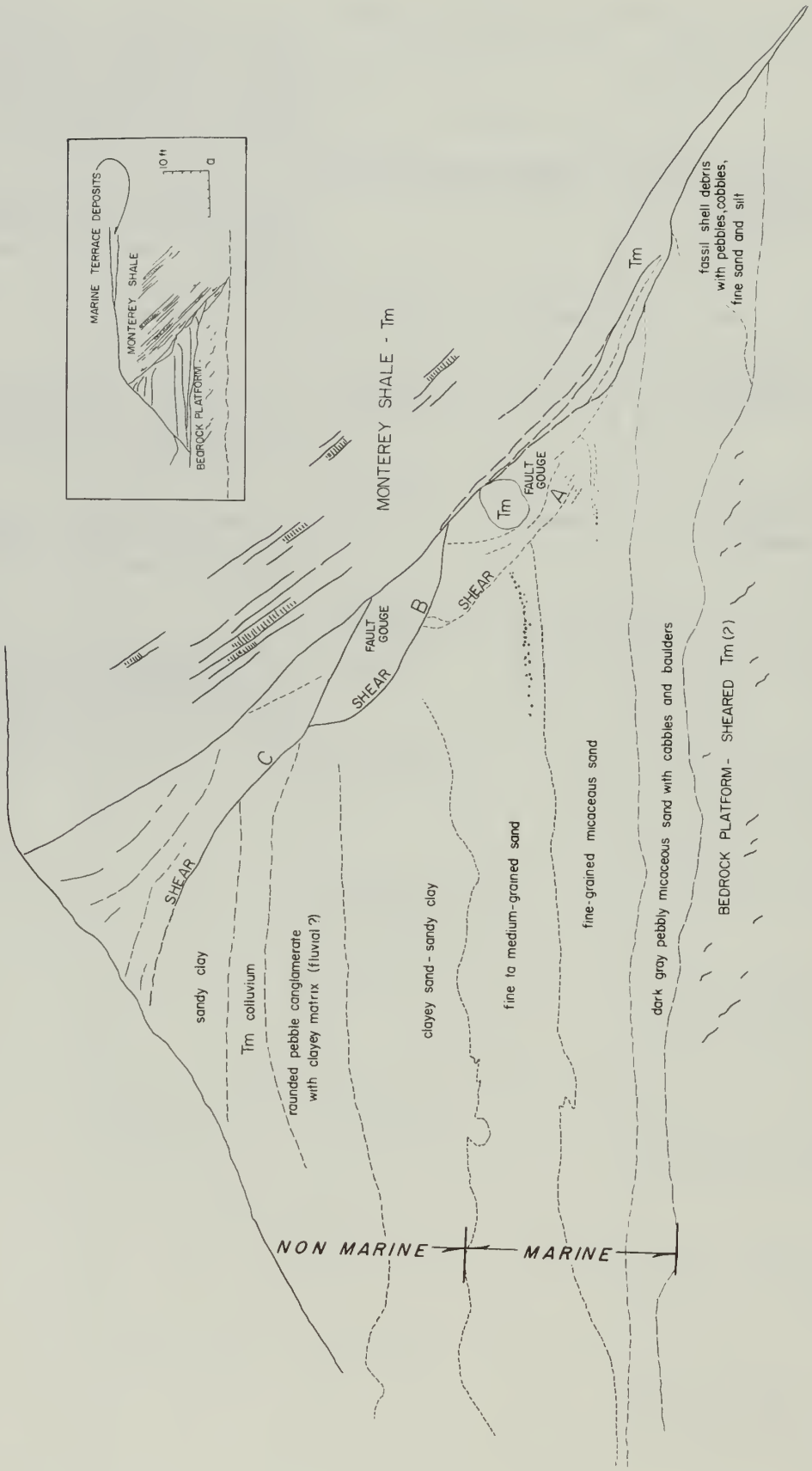

FIGURE 2. Thrust fault near Point Año Nueva. Crass-section of seacliff exposure and generalized marine terrace stratigraphy. Inset map shows complete exposure. The Sangamon(?) terrace platform was vertically offset 5.2 m with 7.9 m of dip separation. Note that shear surface A is truncated by B which is in turn truncated by C. Three episades of movement are indicated.

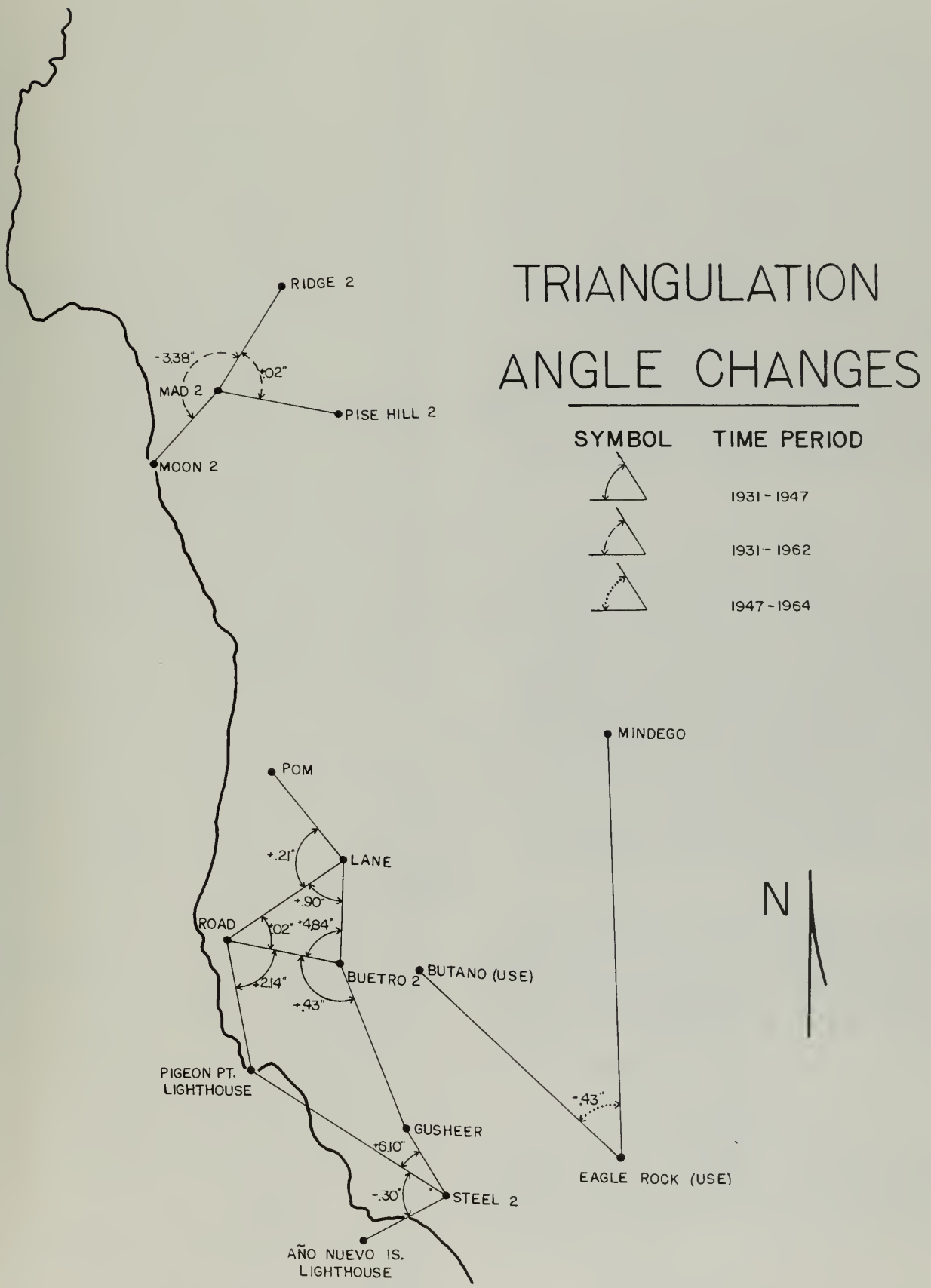

FIGURE 3. Triangulation angle changes taken fram U.S.C. and G.S. unadjusted direction lists. Angles are given in secands af arc.

FIGURE 4. Map of epicenters for the period 1951–February, 1977. Earthquakes in the area of the San Andreas fault and its western branches have not been plotted. Pre–1961 epicenters are shown with open circles. Epicenter location and magnitude data are from: U.C. Berkeley Seismograph Station for 1951–1968; Berkeley supported by U.S.G.S. data for 1969–June, 1975; and U.S.G.S. supported by Berkeley data for July, 1975–February, 1977.

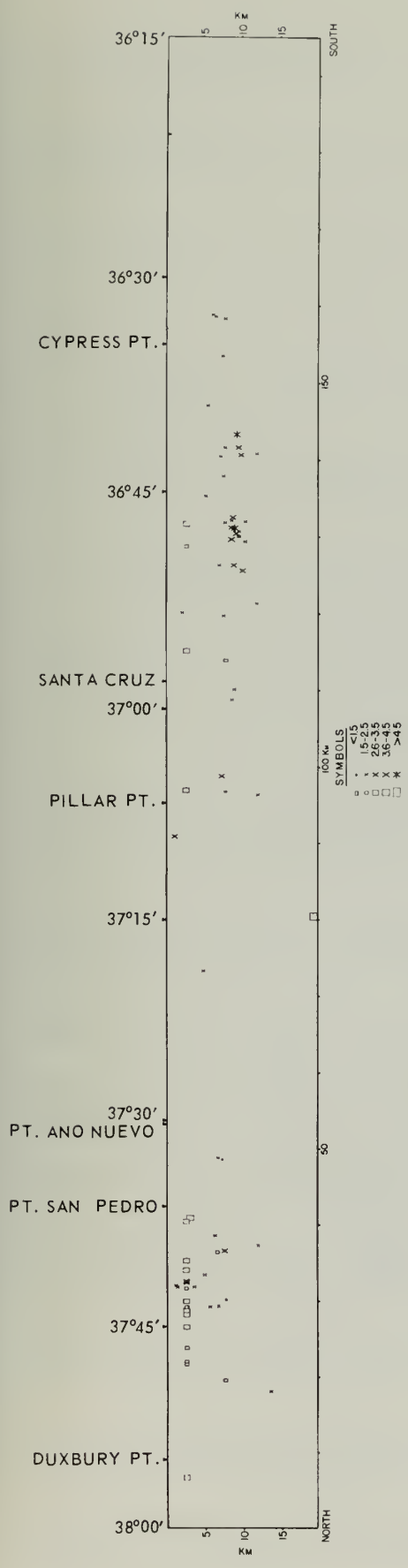

FIGURE 5. Longitudinol cross section of 1962–February, 1977 hypocenters olong the Son Gregorio. Hypocenters 5 km either side of the trend of the fault hove been projected onto o single fault surface. The size of the symbols reflects the eorthquoke magnitude. Rectongles represent 1962–1968 focal depths, ond ore from U.C. Berkeley Seismogrophic Stotion data. 1969–February, 1977 depths ore from U.S.G.S. doto.

with non–vertical nodal planes are compatible with reverse faulting along planes dipping eastward at about 65 degrees. Solutions for earthquakes near Año Nuevo Point are compatible with the thrusting and shortening exposed in the seacliff. Within Monterey Bay, the previously mentioned cluster indicates an average fault plane strike of N15–20°W. This strike is nearly parallel to the trend of the San Gregorio fault zone. In contrast, earthquakes to the south and east show an average fault plane strike of about N60°W. These events may well be related to the Monterey Bay fault zone which crosses the south corner of Monterey Bay and trends obliquely into the San Gregorio.

It is clear that the San Gregorio fault zone is seismically active and that moderately large historic earthquakes have occurred along it. According to Greene and others (1973), based on a fault half–length of 65 to 100 km, an earthquake of magnitude 7.2 to 7.9 could conceivably be generated along the fault. The extension of the fault zone to include the Hosgri system, however, extends the length to over 400 km and further increases the magnitude of the maximum expected earthquake. Wesson (written communication to Hall, Sarna–Wojcicki, and Dupré, 1974) indicates that an earthquake up to 8.5 magnitude could be expected if the fault moves with a significant vertical component.

CONCLUSIONS

The characteristics and behavior of the San Gregorio fault zone shed light on its potential for future activity. It is concluded that:

1. Structurally, the San Gregorio is a complex fault zone up to 3 km wide composed of a number of subparallel traces;
2. A number of traces within the San Gregorio fault zone exhibit late Pleistocene and Holocene offsets;
3. Limited field investigations and triangulation survey data show no sign of fault creep or strain accumulation along the onshore portion of the San Gregorio fault zone. Further resurveying, as well as creep and strain monitoring, may provide more statistically significant results;
4. The fault is associated with recent seismicity. First–motion analysis shows these earthquakes in general to be due to regional right shear and compressional stress.

The San Gregorio is clearly an active fault zone capable of generating moderate to large earthquakes and producing ground displacement. Although the activity along this fault is considerably less than along active portions of the better known San Andreas fault, the San Gregorio fault must be given careful consideration in land–use planning decisions involving critical structures.

Acknowledgments

Special thanks are due to Mr. J. Dracup of the National Geodetic Survey, who furnished the unadjusted triangulation direction lists, and to Mr. R. Lester of the USGS and Mr. R. Uhrhammer of the U.C. Berkeley Seismological Station for unpublished earthquake data.

FIGURE 6. Fault–plane solutions for several earthquakes occurring during the period 1971–February, 1977. Symbols are equal area projections of the lower focal hemisphere. P–wave first motion data from U.S.G.S. and U.C. Berkeley Seismographic Station.

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SEISMICITY AND TECTONICS OF THE CENTRAL CALIFORNIA COASTAL REGION

By William H. Gawthrop*

Abstract

The central Califarnia caastal regian west af the San Andreas fault between Pt. Cancepcian and San Francisca has been studied ta determine the distributian and level af earthquake activity. The histarical recard indicates the accurrence af eight large damaging earthquakes near caastal cammunities. The 1927 Lampac earthquake (M=7.3), lacated near the caast, and the 1926 Manterey Bay earthquake (M=6.1), prabably assaciated with the San Gregaria fault, indicate that caastal faults are capable af generating destructive earthquakes. Recent earthquakes with gaad instrumental caverage, relacated ta maximize lacatian precisian, delineate regians af high seismic activity which carrespand in general ta gealagically mapped narthwest-trending faults.

Facal mechanisms fram 31 events thraughaut the regian indicate a regianal narth-sauth campressianal stress with a campanent af crustal shartening in the nartheast-sauthwest directian. This is cansistent with the trend af falds thraughaut the regian and suggests a simple ane-dimensianal tectanic madel af the plate interactian in central Califarnia, based an simple assumptians af relative plate matian and matian alang the San Andreas fault in the regian af the big bend.

INTRODUCTION

The central California coastal region is seismically and tectonically interesting due to its proximity to the boundary between the Pacific and the North American plates. Relative plate motion in the region is predominantly horizontal dextral shear at a long-term rate of about 5.5 centimeters per year (Atwater, 1970; Minster *et al,* 1974). The San Andreas fault is the major feature accommodating this motion, with a slip rate of about 3.2 cm/yr (Savage and Burford, 1973). The remaining 2.3 cm/yr of relative plate motion is likely being absorbed over a very wide region, with at least some of it occurring to the west of the San Andreas fault in and offshore from central California.

This region is marked by numerous northwest-trending faults striking subparallel to the San Andreas. The mountain folds of the Coast Ranges also trend to the northwest. Many of these folds are Quaternary, and the coast is lined with uplifted marine terraces, indicating recent crustal shortening due to northeast–southwest compression (Ben Page, personal communication, 1975). Most or all of this deformation is due to the regional stress field produced by the plate interaction, which results in earthquake activity throughout the entire region.

Generalizations of fault systems shown in Figure 1 are taken from Jennings (1973) for the onshore area and from Hoskins and Griffiths (1971) for the region offshore. The King City fault system, which follows and may control the trend of the Salinas Valley, runs from Monterey Bay southeast to just north of San Luis Obispo. Little is known about this fault due to the overlying valley sediments obscuring its surface expression. The Sur–Nacimiento and Rinconada fault systems run just inland from the coast and appear to be an intertwining network throughout much of the coastal region covered in this study. The recently discovered Hosgri fault (Hoskins and Griffiths, 1971) appears to be piecewise continuous with the San Simeon and the San Gregorio faults to the north, making up a large fault system following and perhaps causing the trend of the coastline in central California. This system has reported offsets of about 100 km with an average slip rate of about 1.6 cm/yr (Hall, 1976; Graham and Dickinson, 1976), suggesting that it may be accommodating much of the residual differential plate motion in this region of California. The Santa Lucia Bank fault system is located about 100 km offshore, subparallels the coast, and may also be accommodating some residual plate motion.

The seismicity in the region has been previously investigated through concentrated studies of individual earthquake sequences and routine locations of earthquakes by the seismograph networks centered in Berkeley (since the early 1900's), in Pasadena (since 1934), and in Menlo Park (since 1969). Unfortunately, the southern part of the region lies in a gap between seismograph networks. Poor communications between operators of the regional networks resulted in poor location of earthquakes in this area, and several earthquakes with magnitudes greater than 4 were probably never reported by any of the networks. As a result, seismicity maps of California indicate that this region has fewer earthquakes than surrounding regions where seismograph coverage is more complete.

The following sections discuss the locations of some of the larger earthquakes ($M > 5.5$) which have occurred during this century, the locations of earthquakes recorded by local networks, and the focal mechanism solutions of earthquakes throughout the region. The last sections tie this information together with implications of relative plate motions in the area.

LARGE EARTHQUAKES DURING THIS CENTURY

Eight earthquakes greater than about magnitude 5.5 are known to have occurred distinctively west of the San Andreas fault in central California. Due to the low population density of the region, little is known about some of these earthquakes, and some earthquakes larger than magnitude 5.5 in the offshore region during the earlier part of this century may have been missed or unreported. A few apparently very large earthquakes occurred in the region during the last century about which too little is known to include them in this discussion.

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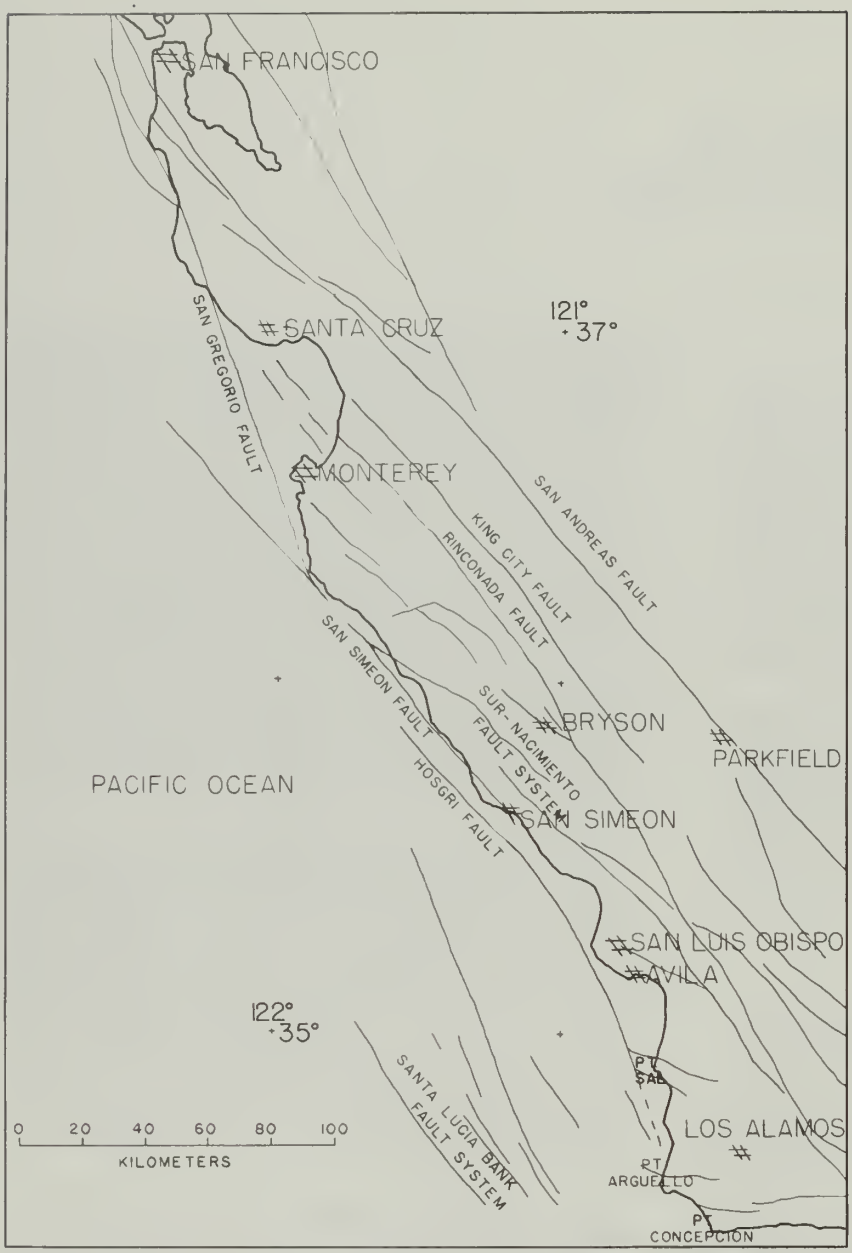

FIGURE 1. Regianal map af the central California caastal regian. Appraximate lacatians af the major fault systems, geagraphical reference points and cities mentianed in text are shawn.

Los Alamos experienced a major earthquake on July 27, 1902, with a Rossi–Forel intensity of IX (Berkeley earthquake file). Surrounding areas had much smaller intensities, so the epicenter was likely near the city. Reports in a local newspaper stated that the nature of the Santa Ynez River changed and that damage was greater on the north side of the river, where chimneys were damaged and several landslides took place. Referring to the Los Alamos Valley, another newspaper reported "a strip of country 15 miles long by four miles wide rent with gaping fissures and dotted with hills and knolls that sprung up during the night...". Based on the description given, the source fault was probably an unmapped fault in or near the Los Alamos Valley which caused severe land deformation, quite likely due to liquefaction, in both the Los Alamos Valley and the Santa Ynez River Valley.

Los Alamos was the location of another severe earthquake on January 11, 1915. This earthquake, with a maximum intensity of Rossi–Forel VIII, was smaller than the previous one, but the distribution of the highest intensities near Los Alamos (figure 2) suggests that the earthquakes were similar and probably originated in the same area. Beal (1915), after an intensive field investigation, determined the epicenter to be a few miles east of Los Alamos based on the distribution of the highest intensities. A fault striking S 82°E, from a map of the Santa Maria oil district (Arnold and Anderson, 1907), was determined to be the source of the earthquake. However, no surface faulting was observed from this earthquake, probably due to the alluvial covering. Chimneys from houses adjacent to this fault reportedly fell in directions approximately consistent with near–field permanent deformation associated with left–lateral faulting. This kind of motion agrees with the focal mechanism of the September 23, 1970, earthquake in the same general area (figure 8).

In 1916, another apparently local shock hit Avila Beach, 16 km southwest of San Luis Obispo. The maximum intensity at Avila was Rossi–Forel VII, with severity apparently increasing towards Port San Luis, to the west of Avila (Berkeley earthquake file). The "San Luis Obispo Tribune" (December 2,

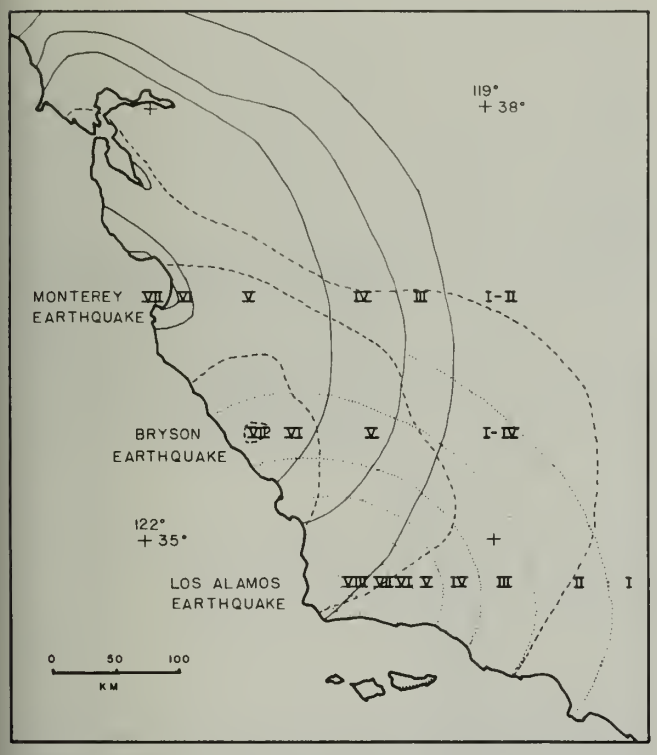

FIGURE 2. Isaseismal cantaurs fram the 1915 Los Alamas earthquake (datted lines–Rassi–Farel intensity scale), the 1926 Manterey Bay earthquake (salid lines–Seiberg intensity scale), and the 1952 Bryson earthquake (dashed lines–madified Mercalli intensity scale). Raman numerals are intensity values which are different far each earthquake and therefore shauld nat be campared.

1916) reported "... an upheaval of the waters in the Bay of San Luis Obispo....". The nature of the upheaval is not known, but it was probably not a large tsunami since it was not reported elsewhere. Again, the low intensities of surrounding towns suggest that the quake was local and probably was caused by a fault in the Hosgri fault system just offshore from Port San Luis.

Two earthquakes with magnitudes greater than 6 occurred on October 22, 1926, in Monterey Bay. Mitchell (1928) made a detailed study of the intensities (figure 2) and found that both Monterey and Santa Cruz had intensities exceeding VII on the eight–point Sieberg scale (Sieberg, 1923). Mitchell reported arrival times of several of the seismic waves of the larger shocks of this sequence at seismographs in Berkeley, Mt. Hamilton, and Pasadena. Improvements on Mitchell's locations were made by inverting P–wave arrival times from these three stations and the S–wave arrival times at Mt. Hamilton for the locations of the epicenters. A crude seismic velocity structure was used which was derived from recent well–located earthquakes reported by these three stations, in addition to numerous stations in the U.S. Geological Survey network. The two largest earthquakes of the 1926 sequence were located within 5 km of the mapped trace of the San Gregorio fault about 15 km northwest of Monterey, with location errors possibly on the order of tens of kilometers. Two aftershocks, which occurred two days and four months, respectively, after the mainshocks (located without Pasadena), lie about 20 km northwest of Santa Cruz and are still within 5 km of the San Gregorio fault. If these events are part of the main sequence, a 40–km rupture along the San Gregorio fault is implied to be the cause of this earthquake sequence.

The largest of the earthquakes recorded in the region of study and the third largest earthquake to have occurred during this century in California is the November 4, 1927, Lompoc earthquake (M=7.3). Byerly (1930) listed intensities at nearby areas and reported an epicentral location about 70 km west of Point Arguello (figure 3) based on arrival times at three seismograph stations–at Berkeley and Mt. Hamilton of the Berkeley network, and at Tucson, Arizona. Because the regional velocity structure of the earth is now better known, the location accuracy could be improved (Gawthrop, 1977). The mainshock was relocated to near the coast just west of Point Sal using seismographs primarily at teleseismic distances and utilizing a quasi–master event relocation technique with the two mainshocks of the 1969 Santa Lucia Bank earthquake sequence (Gawthrop, 1977). There is a 95% confidence that the epicenter was located in the region indicated by the large ellipse in Figure 5. S–P time intervals from aftershocks recorded at a seismograph at Santa Barbara determined the radial distance to many tens of aftershocks. The arcs drawn in Figure 3 show the approximate distances to the nearest and the farthest aftershocks, indicating the probable limits of rupture. This earthquake was probably caused by a 50– to 70–km rupture of a fault near the coast, possibly the Hosgri fault.

On November 22, 1952, a magnitude 6 earthquake occurred near Bryson. This earthquake was located, both teleseismically and with the regional network (discussed in the next section), a few kilometers east of San Simeon. Isoseismal contours taken from *U.S. Earthquakes* (figure 2) indicate that a rupture on an inland fault was responsible for this earthquake.

A sequence of earthquakes with two mainshocks (m_b=5.4, 5.8) occurred in late 1969 in the vicinity of the Santa Lucia Bank. The two mainshocks were relocated using over a hundred seismograph P–wave arrival times at distances greater than 30°. The 95%–confidence ellipses for these earthquakes, based on an assumed reading and timing error of 0.3 seconds, are shown in Figure 3. The confidence ellipses do not take into account possible lateral variations in the velocity structure. Focal mechanisms for these two earthquakes, determined using first motions of the P–waves at seismographs at all distances and by synthetic modeling of the P waveform at 15 seismographs in the Worldwide Network of Standardized Seismographs (WWNSS) by a method described by Herrmann (1976), indicate nearly pure thrust motion on a northwest–trending fault (Gawthrop and Engdahl, 1975). Better recorded aftershocks of this sequence were relocated using a master event technique with the mainshocks. The relocated aftershocks resolved a rupture length of approximately 20 km along a northwest–trending thrust fault in the Santa Lucia Bank region.

Unfortunately, less than 80 years of reliable data is available in the central California coastal region, which is insufficient to derive an upper magnitude limit for earthquakes in this region. However, the magnitude 7.3 Lompoc earthquake with a rupture length of about 50–70 km, and the magnitude 7.7 Kern County earthquake of 1952 to the east of the San Andreas fault with comparable rupture length, indicate that earthquakes in the high 7's are possible in this part of California. There is no evidence that a magnitude–8 earthquake is impossible west of the San Andreas fault.

SEISMICITY RECORDED BY REGIONAL NETWORKS

A regional network of seismographs has been operating since 1932 with the Berkeley stations to the north and east and the Caltech stations to the south and southeast. The southern part

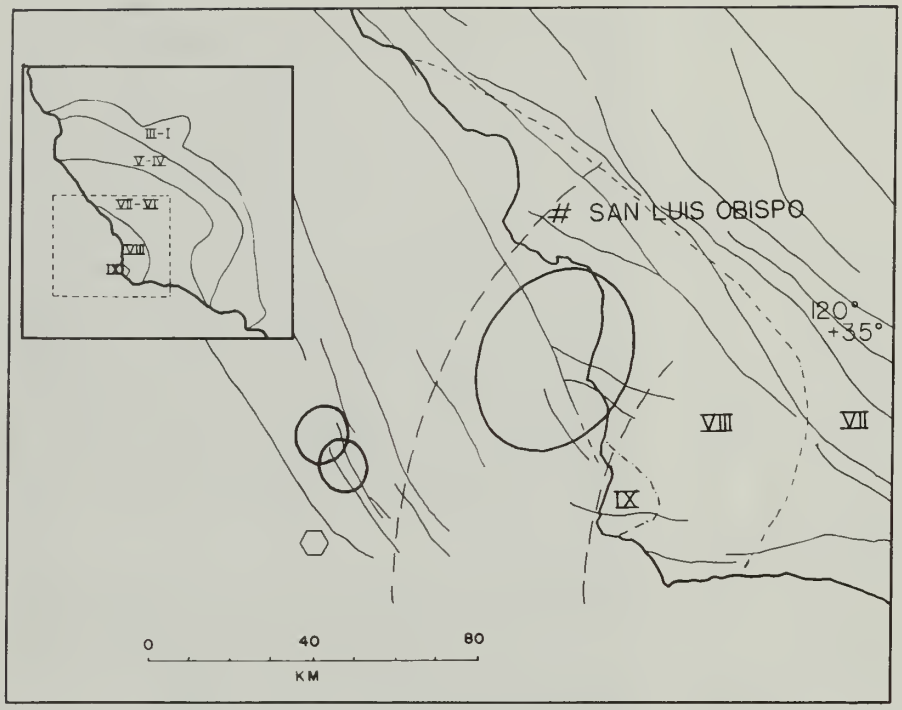

FIGURE 3. Locations and 95% confidence ellipses for the 1927 Lompac earthquake and the 1969 Santa Lucia Bank earthquakes. Dashed arcs indicate maximum and minimum distances of aftershocks of the 1927 earthquake from Santa Barbara. Inset shows Rossi–Forel intensities for the 1927 earthquake. Byerly's (1930) location for the 1927 earthquake shown by hexagon.

of the central California coastal region is between the two groups and little routine effort has been made by either group to accurately determine epicenters in this region (Roy Miller, personal communication, 1974; Richter, 1969). The U.S. Geological Survey (USGS) has operated a dense local network in the northern part of the study region since 1969. The data for relocating epicenters in the southern half of the region, south of 36° N. latitude, were collected for earthquakes between 1934 and 1974 at all three network centers. Some of the arrival times and first–motion data were reread to improve the accuracy and to estimate the reading error. Earthquakes in the northern half of the region recorded by the USGS central California network were relocated as an independent data set with an independently derived velocity structure for the relocations.

Earthquakes used in the southern study were those for which P–wave arrival times were catalogued by Berkeley, Caltech, or the USGS. Since a number of events in the central coastal region are known to have been timed by only one of these groups, it is quite likely that several events have not been timed or located at all. No attempt was made in this study to recover unknown events; however, a search for reports of felt earthquakes in newspapers or in *U.S. Earthquakes* might be productive. It is therefore difficult to determine how complete the data set is, although some estimates of completeness for events over a certain magnitude during a given time interval can be made on the basis of the available station distribution. Because of the labor and difficulty in determining the number and size of earthquakes not catalogued, all statements in this paper about the completeness of the data are merely the best estimates of the author.

The historic record of earthquakes in the central coastal region is more complete for smaller magnitudes as one proceeds from 1934 to 1974 because of the continual expansion of the Berkeley and Caltech networks and the introduction of higher gain seismographs at several sites in California. The best estimates of the thresholds for completeness are magnitude 4.0 since 1940 and magnitude 3.5+ since 1962 for onshore areas, and about 5.0+ and 4.0+, respectively, in the offshore region. The USGS networks south of San Luis Obispo and along the San Andreas fault north of Parkfield, which have been operational since 1969, are very localized networks, so the magnitude threshold for the over–all region has not improved significantly since 1962. The Berkeley network assumed responsibility to insure the completeness of the data in the region around San Luis Obispo in January 1975 (Roy Miller, personal communication, 1975).

The master event technique used for the relocations utilizes one or more well–located earthquakes (master events) to determine for each seismograph station the difference between the actual travel time from a source region to the station and the travel time calculated from an assumed velocity model. Delays are incorporated into the crustal velocity model to account for the travel time differences, or residuals, of the master events and are used to determine the best relative location of the other events in the same region. Using this method, the relative precision of epicenter locations is increased so that the resolution of the data is improved.

All relocations based on regional data were made using HYPOELLIPSE (Lahr and Ward, 1978), a computer program for the location of earthquakes using local stations with an assumed crustal velocity model of either constant–velocity, flat–lying layers, or linearly increasing velocity with depth and station travel time delays. HYPOELLIPSE differs from the standard earthquake location program HYPO71 (Lee and Lahr, 1971) primarily in the computational methods for determining travel times and the ability to calculate a 68%–confidence ellipsoid based on an assumed reading error at the recording station.

Errors in the epicentral coordinates of a shock, assuming correct timing of the P–wave arrivals, are caused by lateral inhomogeneities in the earth's velocity structure, the computed epicenter having been mislocated in the direction of the higher velocities. The computed locations will be mislocated to the west of the actual epicenters if the crustal structure at depth thickens to the east, as might be expected along the continental margin in the region of study.

A crustal velocity model for the central California coastal region was determined by averaging the interpretations of Prodehl (1970) for three refraction profiles near the area of study: 1) Camp Roberts (60 km north of San Luis Obispo) northwest to San Francisco; 2) Camp Roberts southeast to Santa Monica; and 3) San Luis Obispo east to the Nevada Test Site (Nye County). The three models were averaged and approximated by the horizontally layered model given in Figure 4 (Robert Page, written communication, 1974). This velocity model was assumed to approximate the actual crust at depth throughout the region for the purpose of this study.

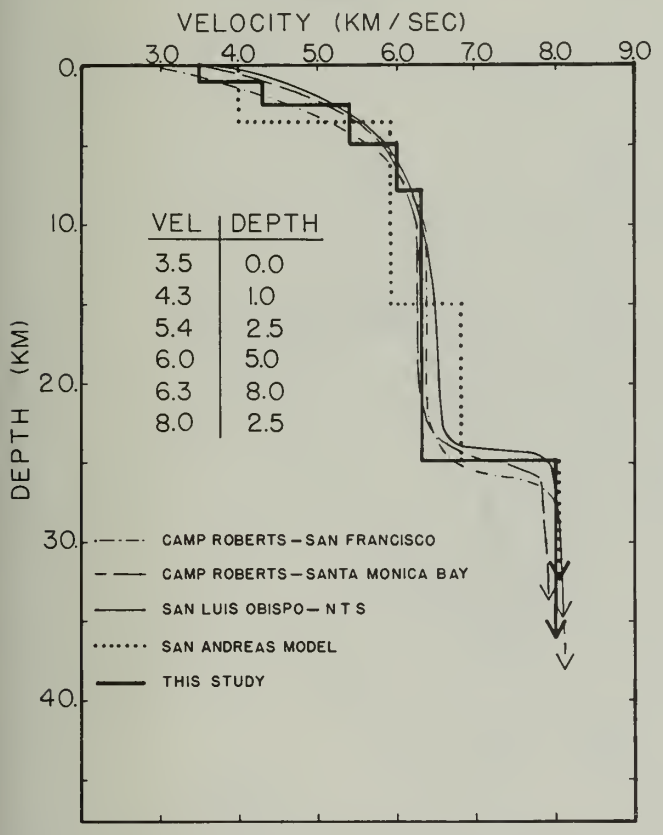

FIGURE 4. Velocity model used for the southern region relocotions. Also shown ore the three models determined by Prodehl (1970) from which this model wos derived ond the stondord USGS central Californio model (Lee *et al,* 1972).

Using a master event technique, delays were then determined for each station to eliminate most of the differences in the local structure under each station and the differences between the actual crustal velocity structure and the structure assumed by the program. Aftershocks from the Parkfield sequence of 1966 along the San Andreas fault at about 36° N. latitude, for which many portable seismographs were deployed near the epicentral region to minimize errors (Eaton *et al,* 1970), were used as master events to determine delays at all California stations operational during the sequence. Delays for stations not operating at that time were determined using several submaster events, relocated using stations for which delays were calculated from the Parkfield aftershocks. Several shocks located throughout the region by the Berkeley and Pasadena stations in 1969 and 1970 were used to determine delays for the USGS stations along the San Andreas fault. Unfortunately, no earthquakes in the southern part of the region were located with sufficient accuracy to determine delays for the USGS stations around Santa Barbara; however, these stations usually had low residuals, so no delays were used. Using these station corrections, all earthquakes were relocated to minimize the relative error in location due to different recording stations for events at different times.

To eliminate misreadings at various seismographs, all residuals greater than 2.0 seconds were given zero weight in the solution of the earthquake after the third iteration. After the program had found the best solution, residuals greater than three times the RMS residual were given zero weight and the relocation process was continued. In this way, most of the larger reading errors are prevented from influencing the final relocation of the earthquake hypocenter.

After the final computer run, the relocations were checked to determine their consistency with the data and poor relocations were discarded. The criteria for discarding relocations were: 1) an insufficient number of recording stations (less than five) over at least 90° in azimuth; 2) an RMS residual greater than 0.6 seconds; or 3) the presence of several arrivals not used in the solution because of high residuals. Approximately 10% of the relocated hypocenters were discarded.

Since few stations existed close to the hypocenters, there was poor depth control on the relocations. All hypocenters in the southern section were arbitrarily fixed at a 7–km depth since this is nearly average for earthquakes along the San Andreas fault to the east (Greene *et al,* 1973). The 68%–confidence ellipses for the epicenter relocations are plotted in Figure 5. Rough lineations of epicenters exist along several faults. Much of the activity is from the San Andreas fault near Parkfield and the vicinity of the Santa Lucia Bank, which includes aftershocks from the 1966 Parkfield earthquakes and the 1969 Santa Lucia Bank sequence. Other epicenters represent background activity and occur along or near the major northwest–trending faults. The confidence ellipses indicate that the weak direction of location accuracy is southwest–northeast, suggesting that northwest trends are significant. The areas along the coast have several epicenters which trend along the Hosgri–San Simeon and Sur–Nacimiento fault systems, indicating that these systems are seismically active. A number of epicenters lie in concentrated groups along the King City fault, indicating that this fault is also seismically active. The region near Point Concepcion has several epicenters with a possible trend to the southwest. This trend is the same as the weak direction of location seen by the confidence ellipses, indicating that the epicentral trend is possibly due to mislocation rather than to a tectonic feature. Only a few epicenters occurred to the southeast of San Luis Obispo; however, this is where the data set is probably the least complete. Reports of felt earthquakes (Townley and Allen, 1939) indicate, however, that many shocks have occurred in this region.

Earthquakes in the northern region were relocated using similar techniques. P–wave arrivals recorded at USGS stations from 1969 to mid–1976 were used to relocate the earthquakes. A lower–magnitude threshold in this region compensated for the shorter recording interval so that a similar number of shocks are reported for both regions. The major difference in the relocation techniques was that a velocity structure of linearly increasing velocity with depth in the crust overlying a constant velocity mantle was assumed for this region. This model can be completely described by only four parameters: the surface velocity, the velocity gradient with depth, the depth to the Moho, and the upper mantle velocity. The model parameters which best fit the observed P–arrival times in the region west of the San Andreas were determined using an inversion technique described by Gawthrop (1976). This best model had a surface velocity of 5.8 km/sec and a velocity gradient of 0.055 km/sec/km. No deter-

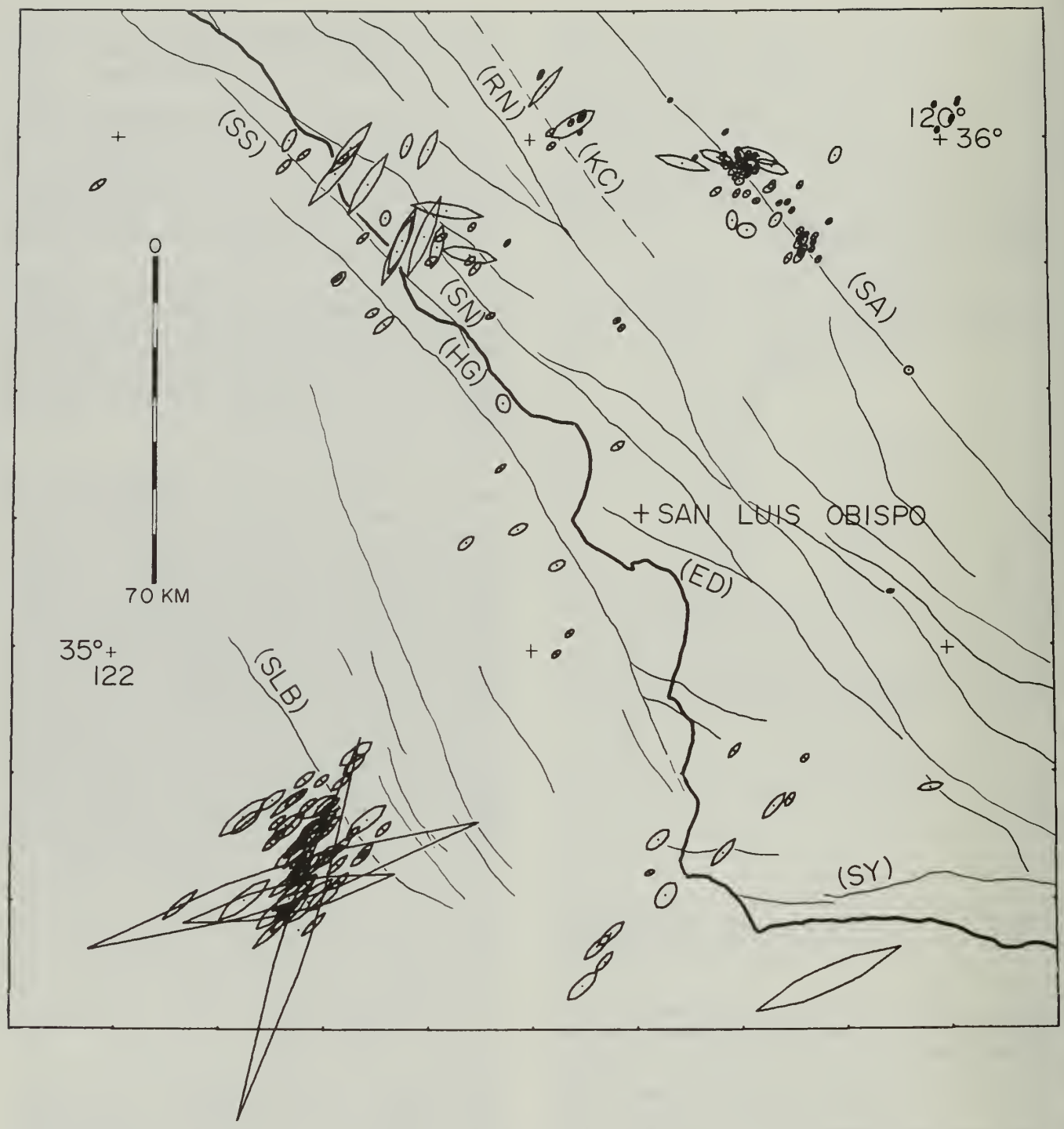

FIGURE 5. 68% confidence ellipses about epicenters from the southern region. Shape of ellipse is a function of station distribution and size is a function of assumed timing error.

mination of the Moho properties could be made from the available data, so Moho depth and P_n velocity were fixed at 25 km and 8.0 km/sec, respectively, similar to the San Andreas model used by the USGS. Delays were again used to minimize RMS residuals in order to maximize location precision. All epicentral locations are plotted in Figure 6, with corresponding 68% confidence ellipses for the better located events plotted in Figure 7.

Again, rough northwest–trending lineations of epicenters occur in the vicinity of the major faults in the area. The confidence ellipses indicate that the weak direction of location is again approximately normal to the lineations, strongly suggesting that the lineations are not artifacts of the location process.

Patterns of seismicity inferred from these plots indicate that the region is subjected to a tectonic stress and is responding with a relatively high background of earthquakes throughout the region. These small earthquakes do not significantly relieve the stress, but do indicate that it exists. Because stress that is currently causing these micro–cracking events is likely to be increasing, future large earthquakes should occur along these zones of weakness to relieve the accumulative stress. Unfortunately, using the

FIGURE 6. Epicenters of earthquakes from 1969 to mid–1976 relocated using velocity model which increases linearly with depth. Only earthquakes catalogued by USGS central California network used in the relocations.

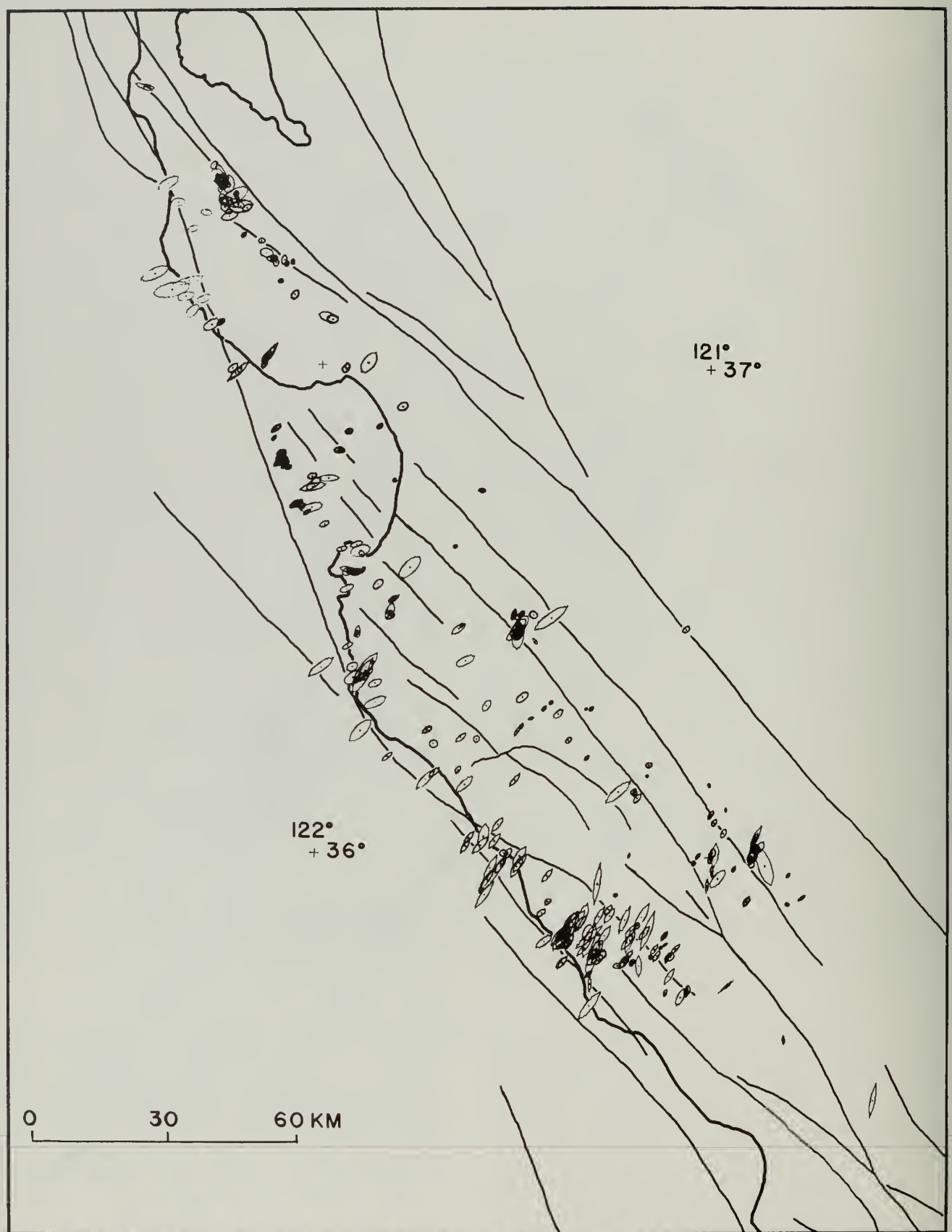

FIGURE 7. 68% confidence ellipses for better quality locations of events in Figure 6. The northeast trend of the weak direction of location indicated by most of the ellipses reflects a lack of station coverage to the southwest.

short–term sample of available earthquakes, it is possible to determine only which fault systems are active. Some faults which are known to have been active in historic time do not reveal themselves to microearthquake surveys, e.g., the seismicity gaps of the San Andreas fault along the 1906 and 1857 rupture zones. A further delineation of the active fault traces would require a higher concentration of seismographs in the region.

FOCAL MECHANISMS

Fault plane solutions for several earthquakes throughout the region were determined using first motion directions from regional seismograph stations. Some of the early solutions depend on just a few readings in a critical part of the focal sphere, so accuracy in reading these first motions is important. The original seismograms were reread whenever possible for positive identification of the direction of first motion at each station. Questionable readings and readings not checked by the writer are given less weight than the well–determined first motions. Some of the more recent mechanism solutions were determined using data routinely read by the USGS network readers and not rechecked by the author. These mechanisms have sufficient data redundancy to minimize the effect of misreadings. Data for these solutions are given elsewhere (Gawthrop, 1977).

All first motions were plotted on the lower hemisphere of an equal area projection of the focal sphere around the hypocenter. Take–off angles were calculated from the crustal velocity model with the linearly increasing velocity with depth over the constant velocity Moho calculated in the inversion. Hypocentral depths were assumed, for ease of calculation, to be 10 km unless sufficient depth control indicated otherwise.

Mechanism solutions for the two mainshocks of the 1969 Santa Lucia Bank sequence were supplemented with data from the WWNSS stations. Synthetic modeling of the P–waveform as discussed in Herrmann (1976) was used to match waveforms recorded at 15 WWNSS stations at teleseismic distances for both events. A very close match of the calculated to the observed seismograms for each event was obtained for focal depths of the point source, double–couple equivalent force at an 8–km depth with an orientation corresponding to nearly pure thrust motion. The relative strikes and dips of the two planes for each mechanism are well determined by this method, but the absolute strikes of the fault planes are poorly constrained. Because the teleseismic locations of the two mainshocks and the trend of the aftershocks discussed earlier line up with the trends of the faults in the Santa Lucia Bank fault system, the strike of the fault planes in both mechanism solutions are taken to be the strike of the mapped faults near this sequence.

Focal mechanisms are plotted as lower hemisphere projections with the shaded quadrants being compressional (figure 8). Well determined solutions with fault planes probably uncertain by less than 15° are plotted larger than solutions that either depend on one or two critically located readings or have fault planes which are uncertain by as much as 20° to 30°. Assuming that the northwest–trending faults are the sources of most of these earthquakes, a predominance of right, oblique slip can be inferred. Most solutions reflect considerable compression normal to the trend of the San Andreas fault. This is best illustrated in Figure 9, where the pressure and tension axes of all these mechanisms are plotted on one projection. All of the pressure axes group in one part of the focal sphere, whereas the tension axes loop around the focal sphere. No significant change of trend is appar-

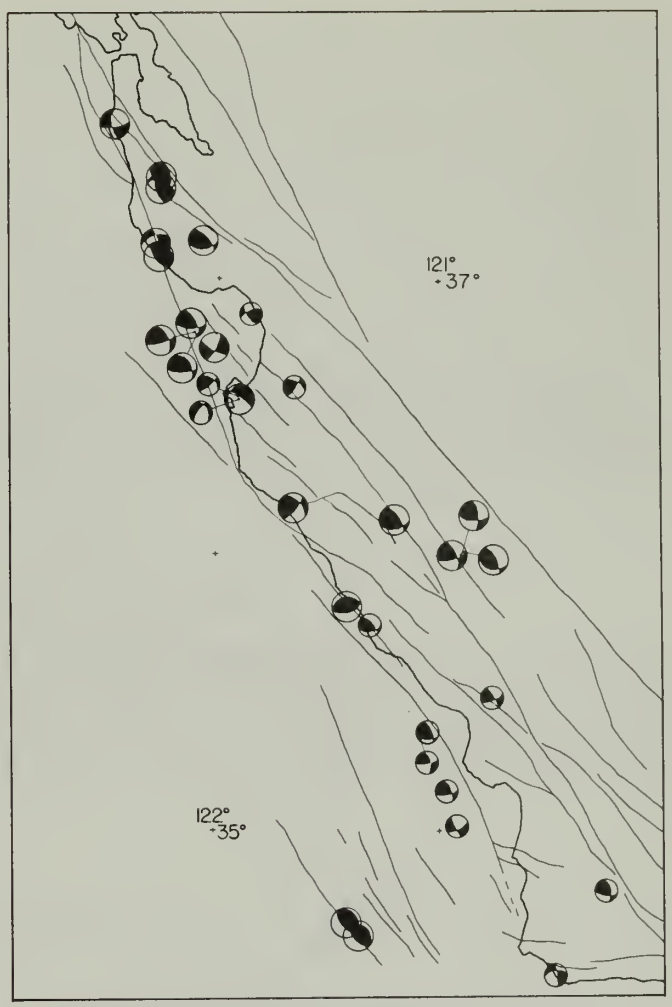

FIGURE 8. Focal mechanisms of earthquakes. Shaded area indicates compressional quadrant in lower hemisphere plot. Large mechanism plots are better determined than the smaller mechanism plots.

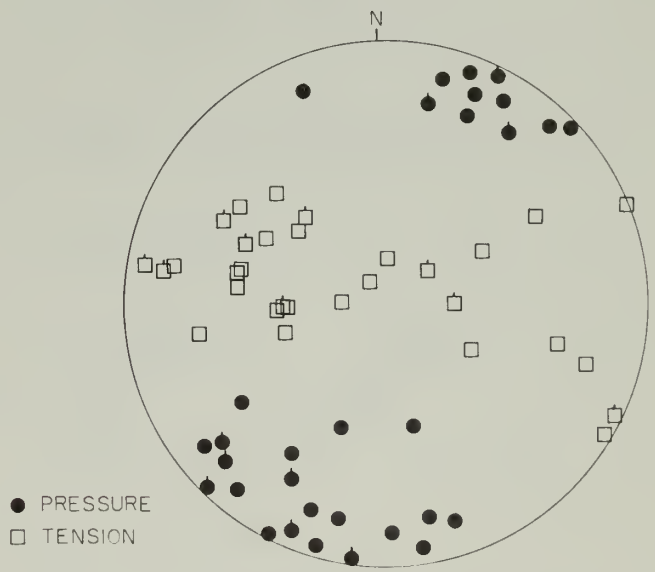

FIGURE 9. Pressure and tension axis plot. Small area of pressure axis on focal sphere indicates that compression dominates the local tectonics. Tick marks indicate the event occurred south of 35° 30′ near the Transverse Range province.

ent between the northern and southern parts of the region. This indicates that the pressure axis, or axis of greatest principal stress, dominates the regional stress with the secondary and tertiary stress directions trading off between horizontal directed stress and vertical lithostatic loading throughout the region. Also, the direction of the pressure axis grouping is rotated about 25° clockwise from the pressure axis trend expected from pure strike–slip motion along the San Andreas fault. This indicates northeast–southwest compression and is supported by the trends of folds in the Coast Ranges (figure 10) taken from Burford (1967). All this data suggests the concept that the plate interaction in California is not pure strike–slip transform faulting, but includes a significant component of crustal shortening in the northeast–southwest direction. This indicates that the relative motion between the Pacific and North American plates is not parallel to the San Andreas fault in the Coast Ranges, as has been previously assumed, but is instead somewhat oblique to the trend of the fault in this region of study.

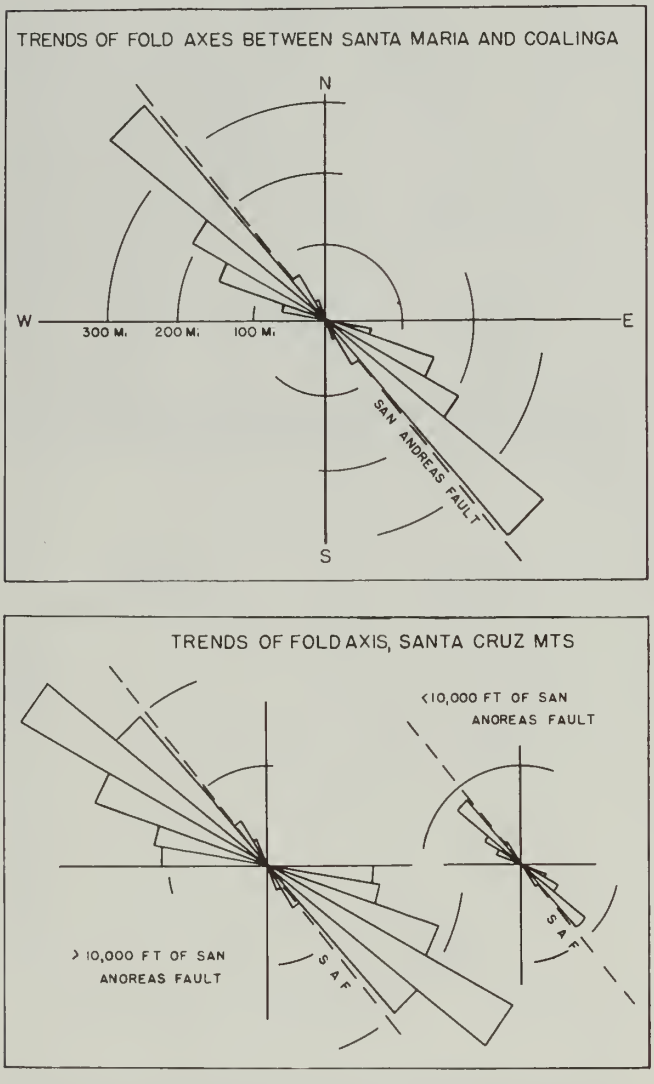

FIGURE 10. Fold axis plot indicating the lengths of folds in the Coast Ranges with a particular trend (from Burford, 1967).

MODEL OF PLATE INTERACTION IN CENTRAL CALIFORNIA

A simple one–dimensional model relates the relative motion vector between the Pacific and North American plates to the slip vector of the San Andreas fault in order to determine a residual motion vector. The San Andreas slip vector is assumed to be of constant magnitude (3.2 cm/yr) to conserve mass, with a direction parallel to the local fault trend. The relative plate motion vector is assumed to be of constant magnitude (5.5 cm/yr) and of constant tangential direction about some pole of rotation on the earth. The difference between these two vectors, the residual motion vector, is the resulting plate motion not accommodated by slip on the San Andreas fault. This vector should, in general, line up with the direction of crustal deformation due to folding and faulting away from the fault. Figure 11 illustrates this model with an assumed plate motion vector, oblique to the trend of the San Andreas fault in the Coast Ranges by 25°, corresponding to the 25° rotation of the pressure axis trend discussed earlier. Also shown are the directions of slip during the 1952 Kern County earthquake (M=7.7) and the 1971 San Fernando earthquake (M=6.6) as determined from focal mechanism solutions. The fit between the observed directions of motion from these earthquakes to that determined by the residual motion vector calculated by the model is reasonable. A better fit could be obtained by further clockwise rotation of the relative plate motion vector.

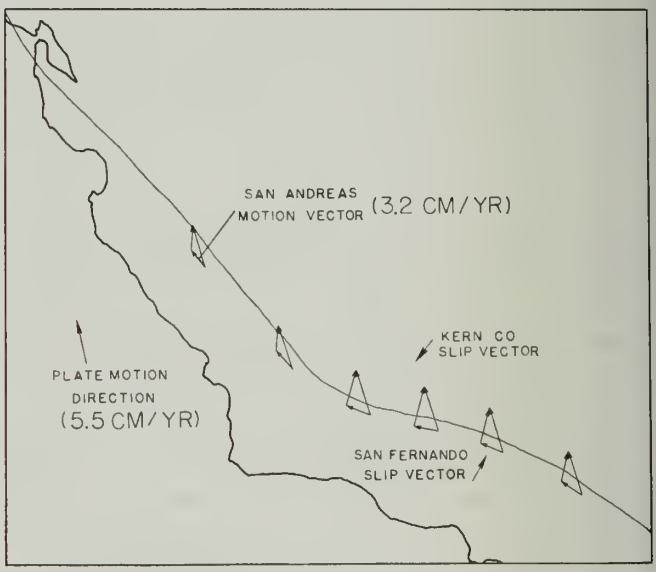

FIGURE 11. One dimensional model of central California tectonics. Plate motion vector and San Andreas slip vector determine the residual motion vector. Slip vectors of large earthquakes in California agree with the residual motion vector for plate motion into the trend of the San Andreas fault in central California.

Minster *et al,* (1974) calculated poles of relative motion of eleven major plates covering the globe. Data for the direction of motion between the Pacific and North American plates came from slip vectors of earthquakes primarily in the Gulf of California and in Alaska. The pole of rotation determined using only data from strike–slip faults indicates that the relative plate motion in California is oblique to the Coast Range trend of the San Andreas fault by only about 5°, with a probable error of ± 10°. Data from thrust earthquakes in the Aleutian Islands, however, indicate that if North America is a single rigid plate which includes Alaska, then this relative motion should be rotated about 10° further clockwise. This value still does not exceed the

25° direction indicated by secondary faulting in central California. The implication is, therefore, that some deformation other than that due to the San Andreas fault is restricting part of the motion, in the same sense as the San Andreas, so that the residual motion is reduced but further rotated in a clockwise sense. The true relative plate motion vector should equal the sum of all deformation vectors across western North America. The model shown in Figure 11 is admittedly a simplification of the complex deformation occurring in the interaction of the two plates, but is probably a good first step in unraveling the over–all deformation.

CONCLUSIONS

A study of the historical record of earthquakes along the central California coast region reveals that the area is seismically very active. During the last 80 years, one magnitude–7 earthquake and several magnitude–6 earthquakes occurred on faults west of the San Andreas fault. The possibly continuous Hosgri–San Simeon–San Gregorio fault system is likely responsible for a large part of this activity. The regional seismicity pattern indicates that most of the earthquake activity is occurring along several northwest–trending faults throughout the region. All of these faults are subjected to an apparently nearly uniform stress field, so any of them could break to help relieve the accumulated regional stress. At least some of the 2.3 cm/yr of relative plate motion not attributable to the San Andreas fault must be relieved in this manner.

Focal mechanisms throughout the region suggest that the driving motion is not parallel to the San Andreas fault or the strike of the faults to the west, but has a component normal to these faults, resulting in some thrust faulting and folding. A simple one–dimensional model of the plate interaction in California indicates that the relative motion vector is oblique to the main trend of the San Andreas fault in central California. Left–lateral faulting activity in the Transverse Ranges can also be explained by this model by noting the direction of the residual motion vector relative to the fault trends, provided that some thrust faulting accommodates this type of motion.

There is no reason to expect that earthquake activity in the region during this century has been abnormally high. Future earthquakes of magnitude 7 or greater, similar to the 1927 Lompoc or the 1952 Kern County earthquakes, should be expected along faults in this region. If continuous, the Hosgri–San Simeon–San Gregorio fault system is long enough to produce magnitude–8 earthquakes. With an apparent slip rate of about 1.6 cm/yr, it is possible that a magnitude–8 earthquake, rupturing in excess of 200 km of this fault with greater than 4 m of displacement, could recur every 250 years.

The likelihood of magnitude–8 earthquakes on this fault, or on any other large fault in this region, is a function of the strength of the fault system and its ability to rupture for distances in excess of 200 km. Future earthquake activity should be regarded as a major hazard when considering the future development of this region.

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